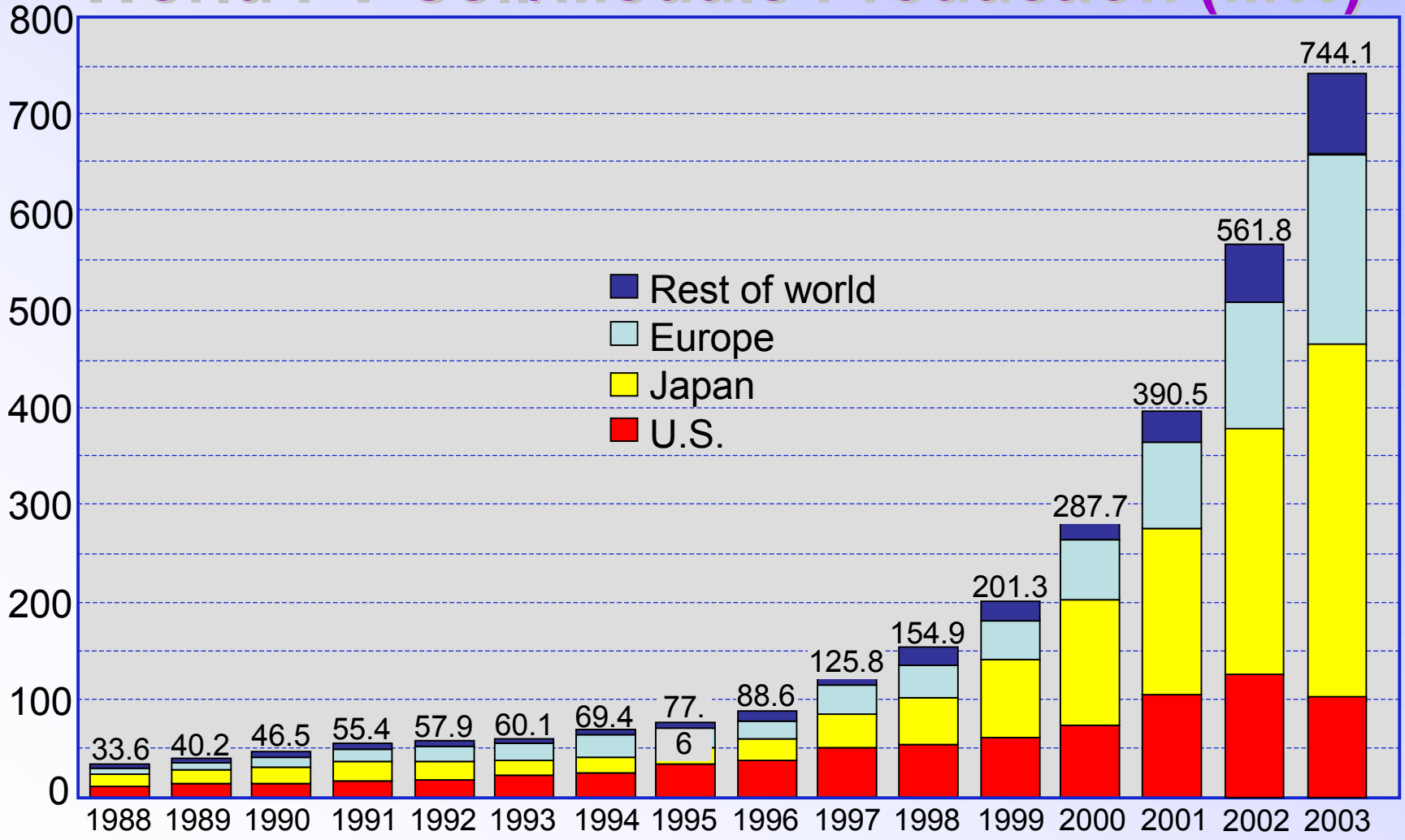
National Center for Photovoltaics

NREL Technology Day May 19, 2004

John P. Benner, Manager Electronic Materials and Devices Division

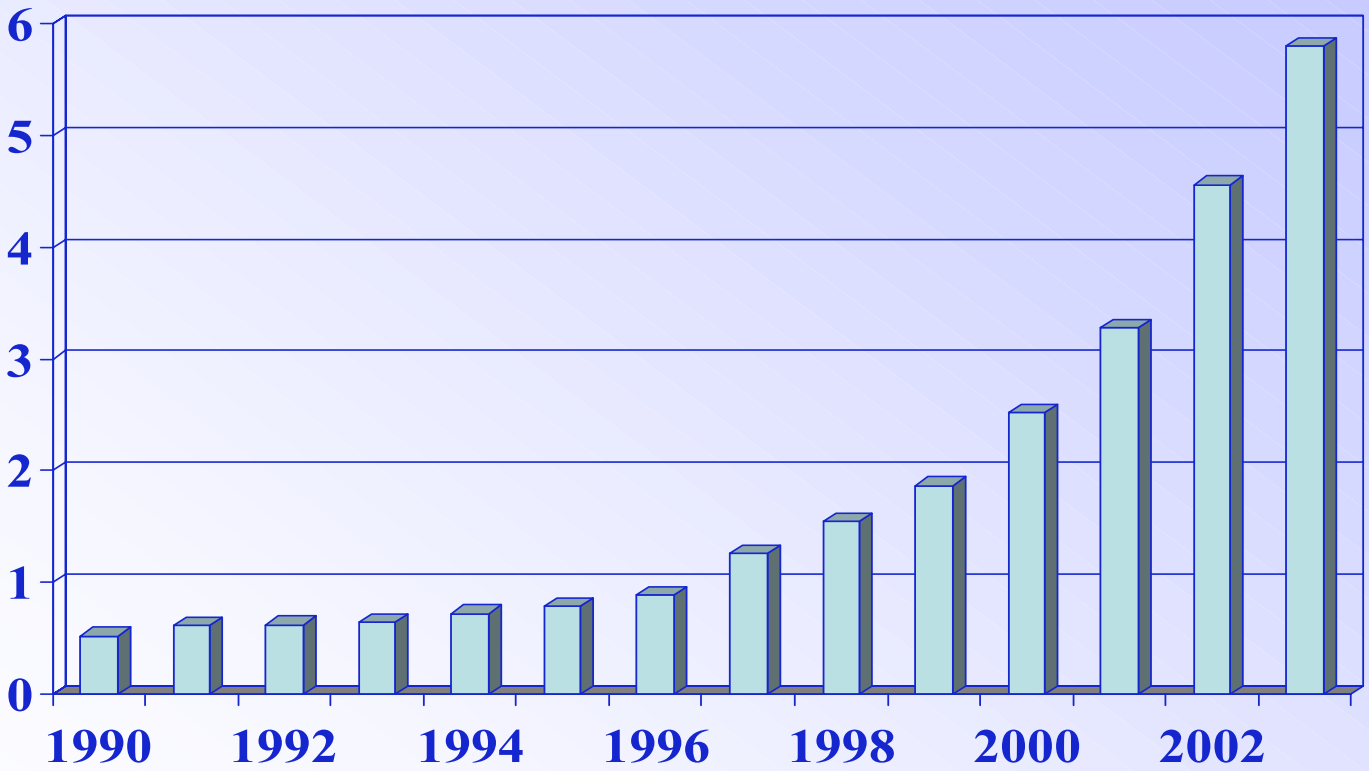
Office of Energy Efficiency and Renewable Energy

World PV Cell/Module Production (MW)

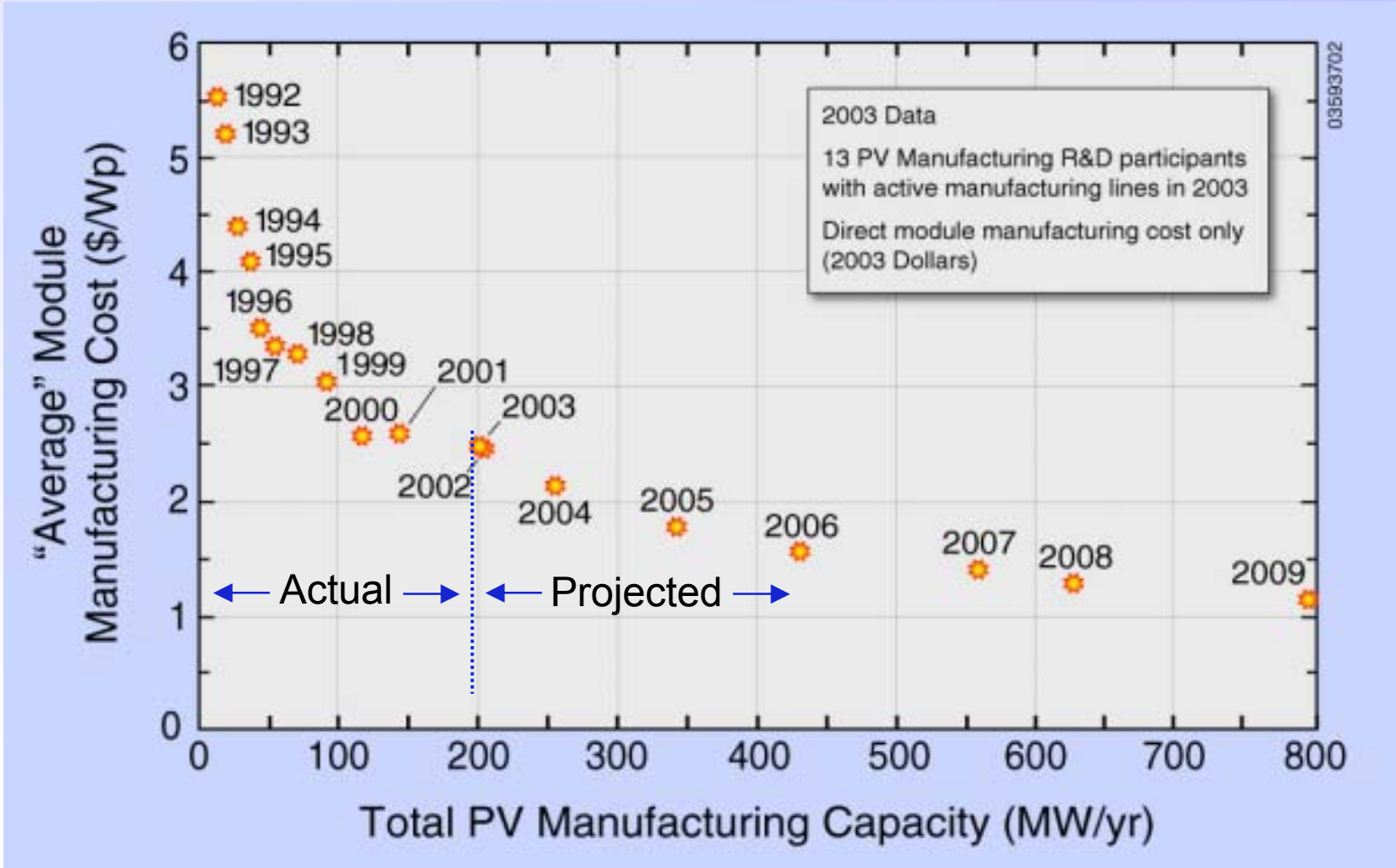


Source: *PV News*, March 2004

World PV Systems Sales ($B)

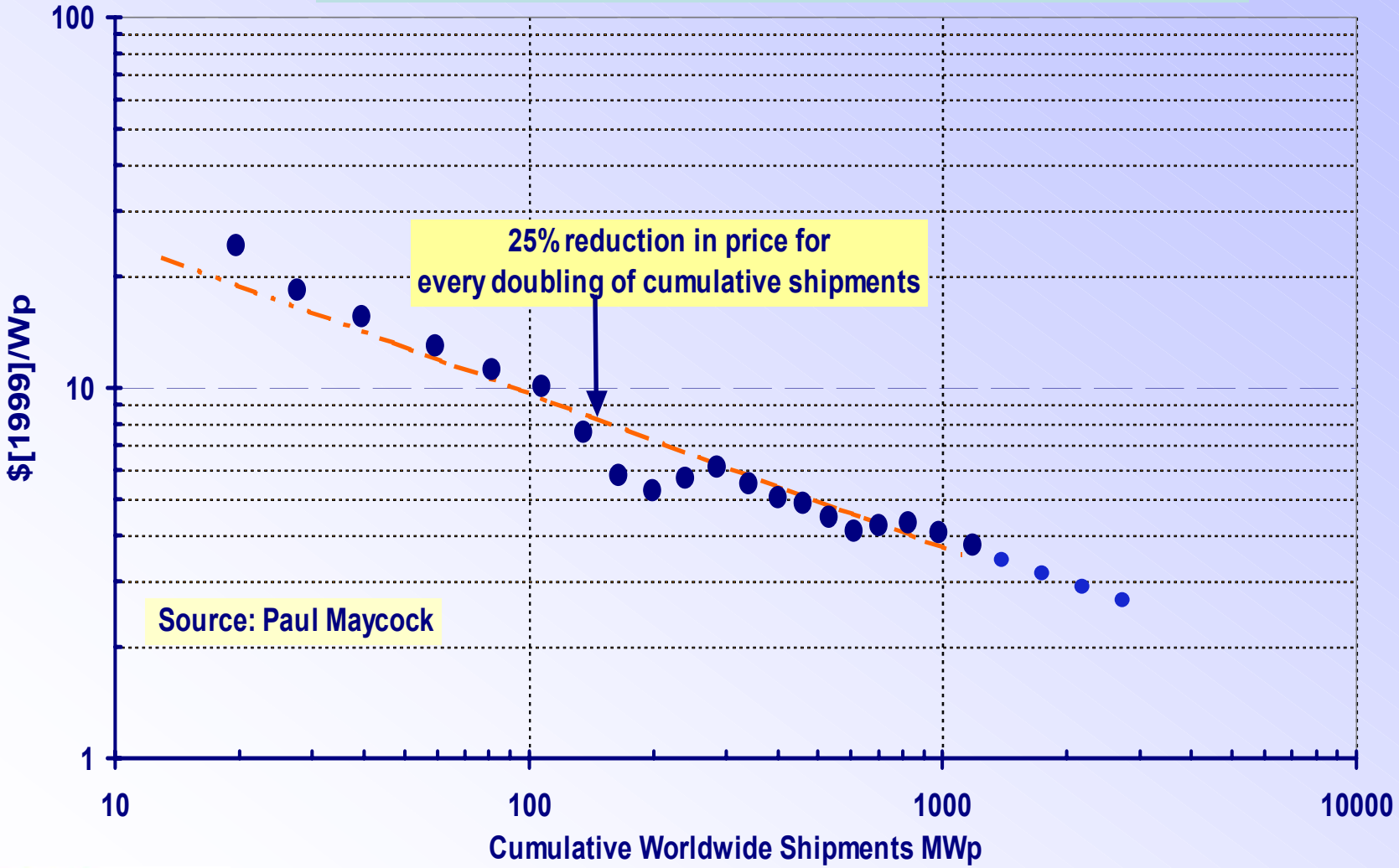


PV Manufacturing R&D Cost/Capacity

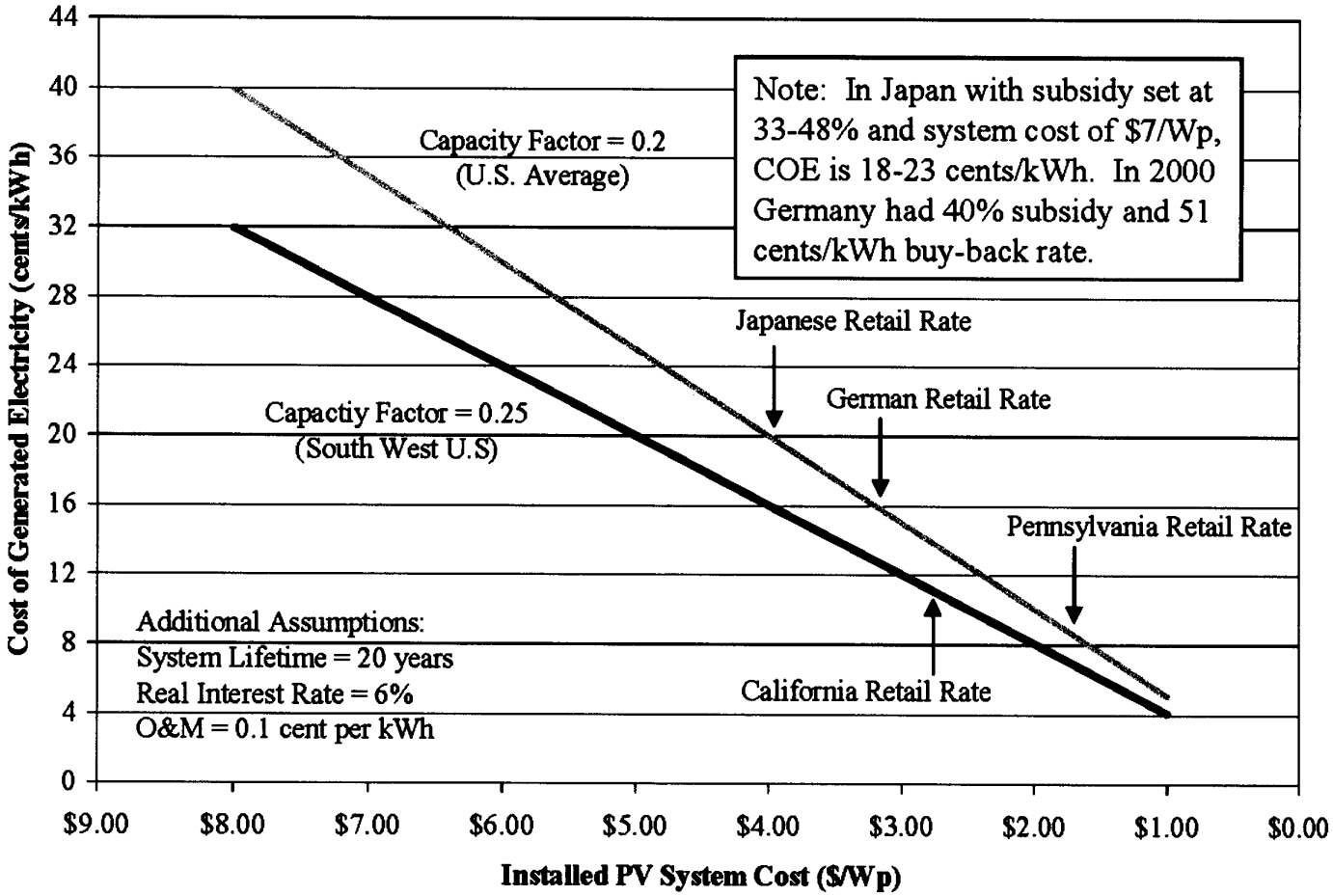


PV Manufacturing Research Data (DOE/U.S. Industry Partnership)

Reduction in Module Price versus Cumulative Shipments Experience Curve



PV System vs. Electricity Costs

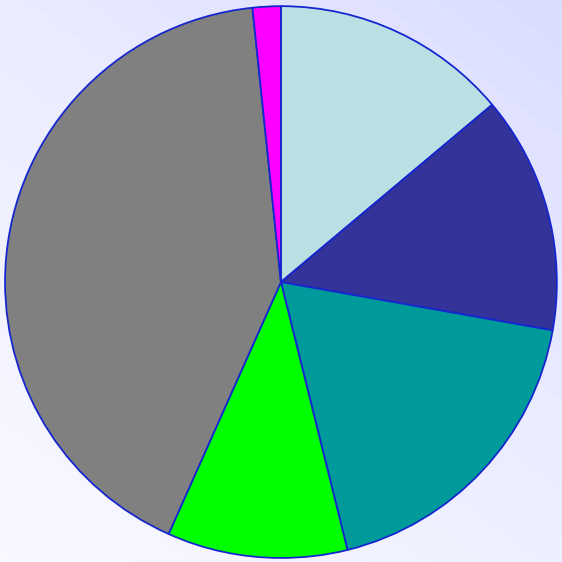


R. M. Margolis, NREL Presentation, March 24, 2003, page 15

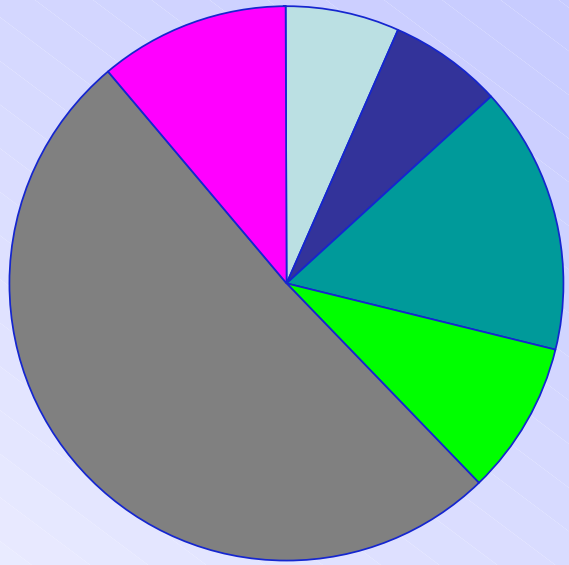
PV Market Sectors

NCPV

2000 Actual 0.3 GW



2010 Projected 4.5 GW



- Consumer
- Communication
- Off Grid
- Hybrid/Commercial
- Grid Connected BIPV
- Utility Scale

NREL National Renewable Energy Laboratory

Changing Landscape of Electric Power

NCPV

- Natural Gas Shortage
- Transmission and Distribution Limitations
- CEO's Call for National Energy Strategy
  - - With Balance
- International Pressure on Global Climate Change
- State and Local Initiatives for Renewable Energy

NREL National Renewable Energy Laboratory

What is this NCPV?

NCPV

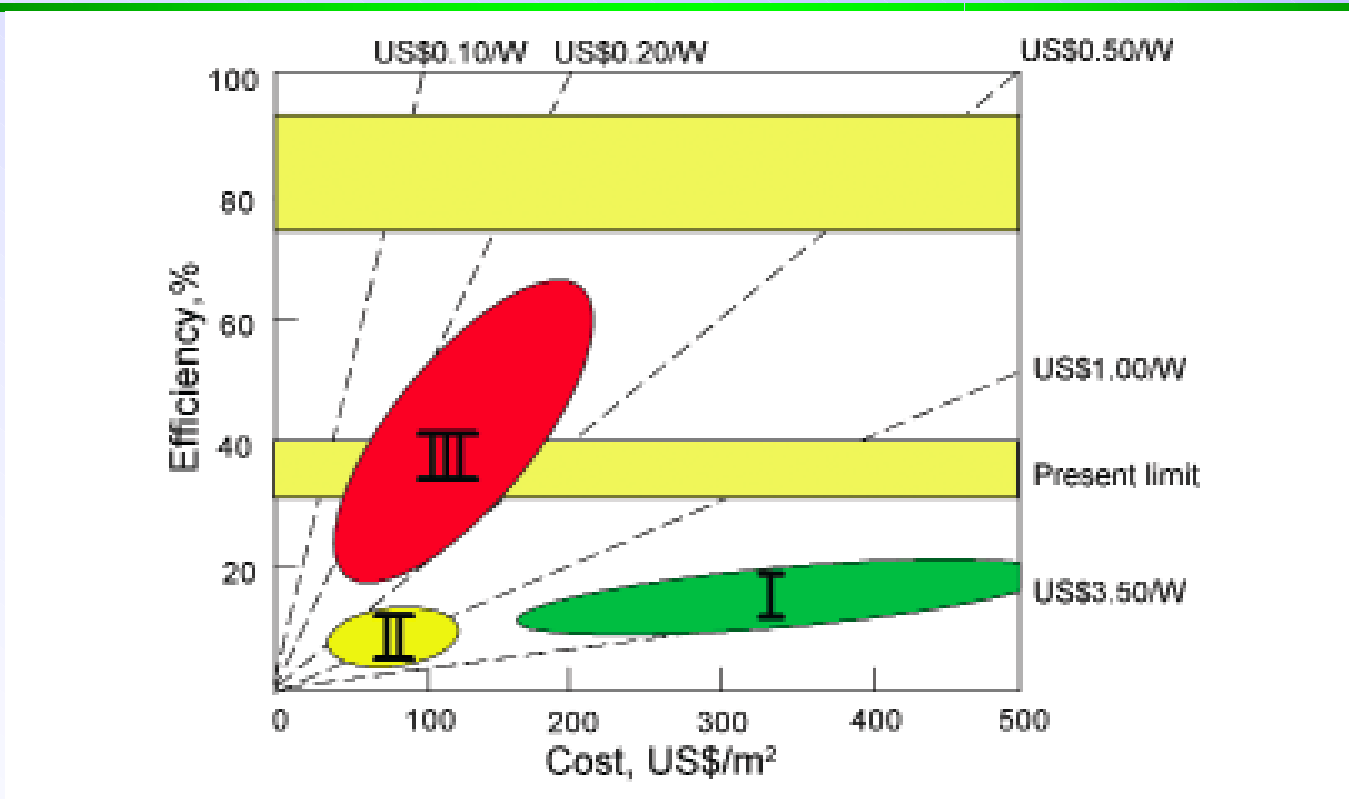
The *National Center for Photovoltaics* is the organization established by the DOE to lead the U.S. photovoltaic efforts

- in performing world-class R&D,
- promoting partnering and growth opportunities,
- serving as a forum and information source—

To guide and assist the U.S. photovoltaic activities toward maintaining and enhancing technological and industrial leadership.

Efficient Solar Electric Conversion

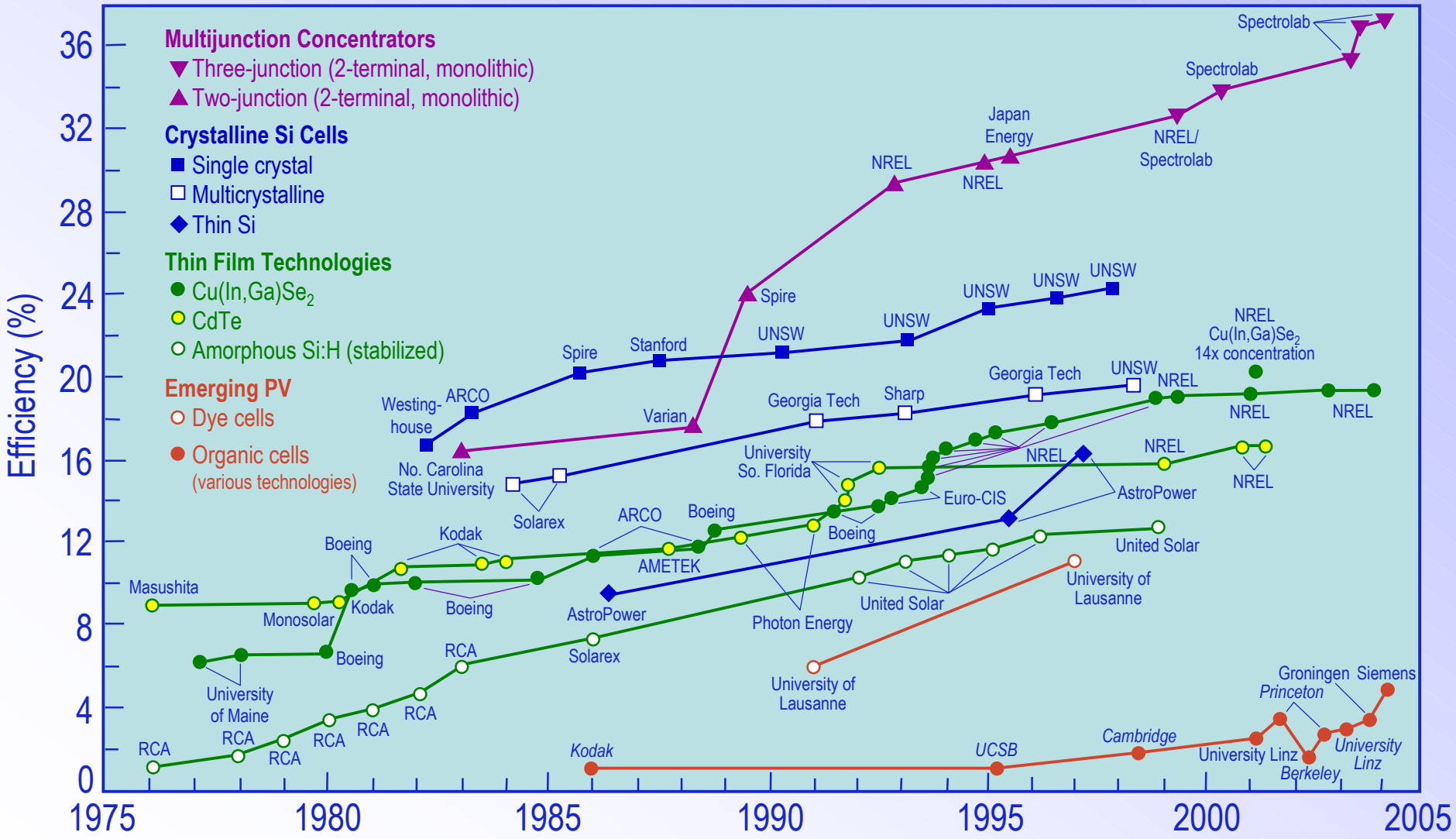
NCPV



- Current technologies need improved manufacturing processes
- 3rd generation technologies demand both very low cost and very high efficiency

Best Research-Cell Efficiencies

NCPV



NREL National Renewable Energy Laboratory

Discovery Mode Technologies

NCPV

Absorber		Charge Transfer
Organic/Metalorganic Dye	⟷	Nanostructured Inorganic
Inorganic particle	⟷	Inorganic matrix
Inorganic particle	⟷	Polymer
Organic particle	⟷	Polymer

Small Molecule Organic

Polymer

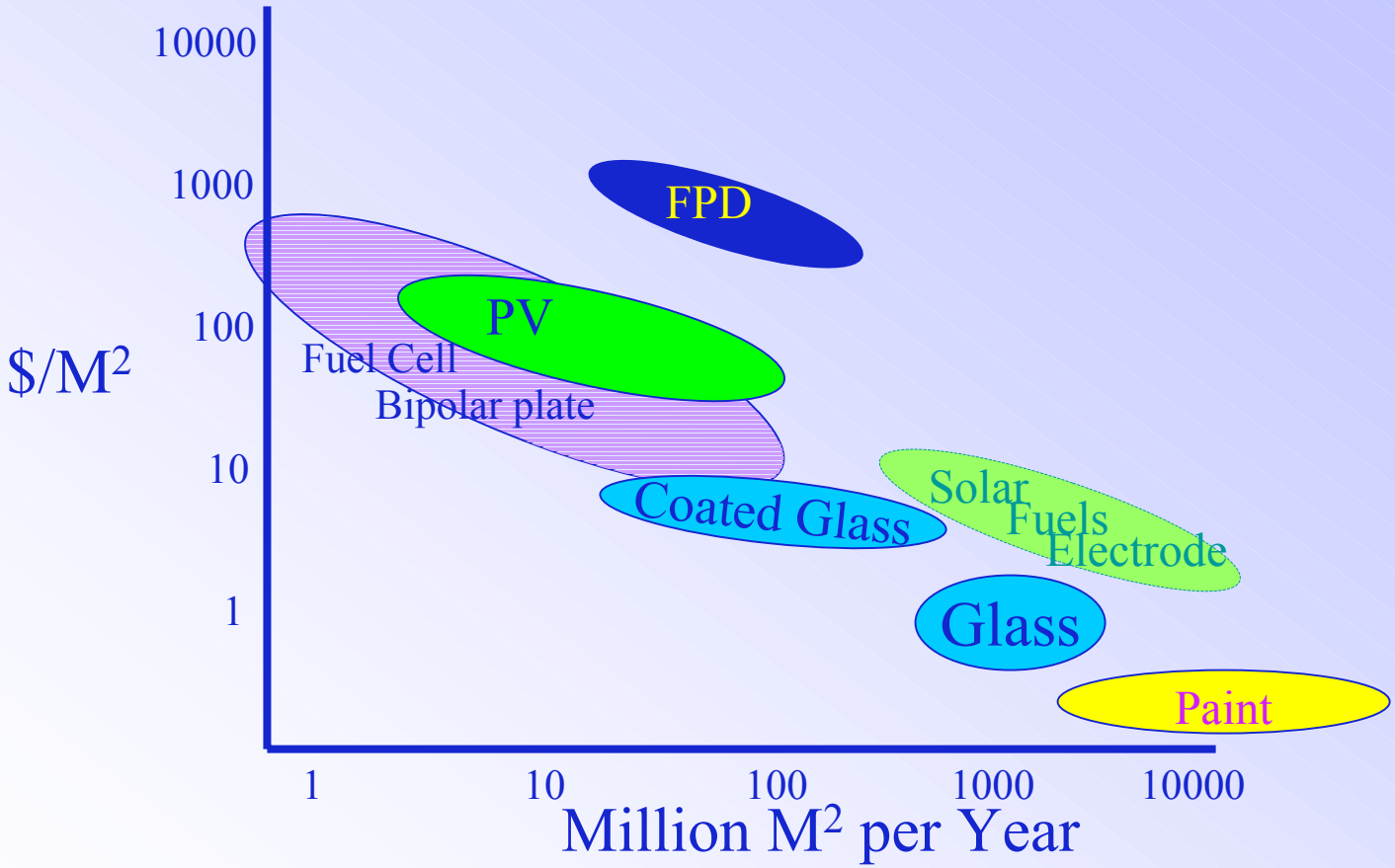
Low Cost Processes

NCPV

Space PV

LED

Large-Area Optical and Electronic Materials



NREL National Renewable Energy Laboratory

Reliability and Performance

NCPV

NREL National Renewable Energy Laboratory

PV Summary

NCPV

- PV Business is a Business
  - Market acceptance;
  - >$5B sales
  - New corporate sector investments
- NREL's research in first, second and third generation PV materials and processes provides infrastructure for nearer term PV and non-PV product development


The NCPV Focus
Helping to make PV the power of choice . . .

NREL/ReflecTech Silvered Film

NCPV

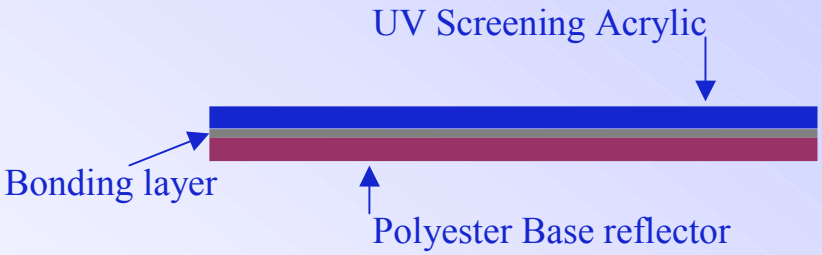
A better reflector for outdoor mirrors.

7+ year development program just completed.

Glass mirrors are the status quo, but are heavy and expensive.

Reflective Film Properties & Applications

NCPV



- High Solar Reflectance
  - 94% Specular Reflectance (25 mrad)
  - 94.5% Hemispherical Reflectance
- Excellent Outdoor Weatherability
  - 10+ year UV stability
  - NREL and Independent Lab Testing
- Low Production Costs
  - Partnership with Bakaert
  - 60 inch wide rolls demonstrated

- ✓ Solar trough & dish
  - Solargenix
- ✓ Daylighting
- ✓ Thermal control

NREL National Renewable Energy Laboratory

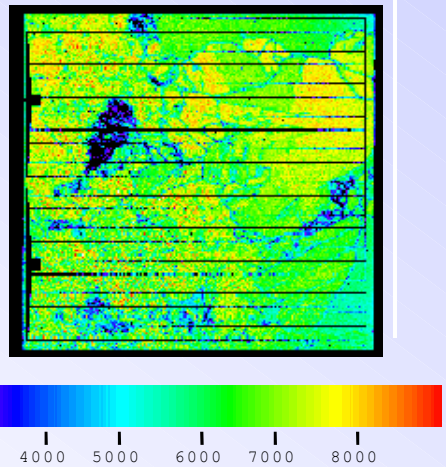
High Throughput Optic-based Production Monitors

NCPV

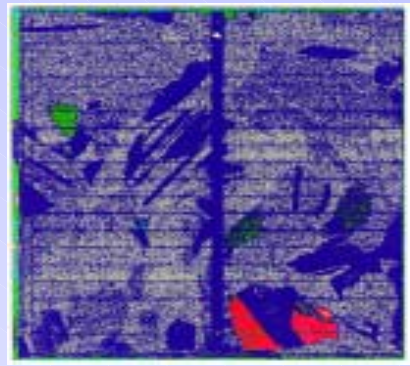
- Defect (dislocation) density, grain boundary distribution
- Reflectance (specular, near-specular, and diffuse)
- Light Beam Induced Current (LBIC)

NREL National Renewable Energy Laboratory

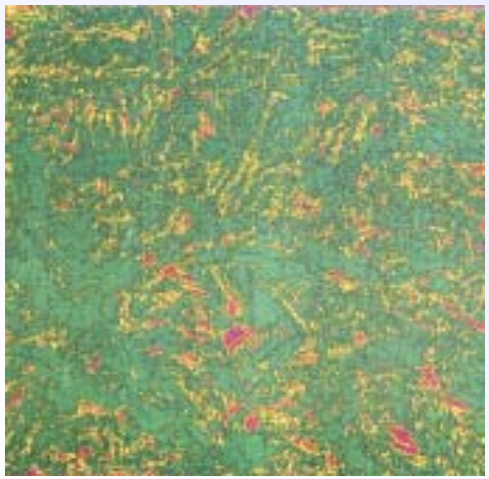
Light Induced Current Map



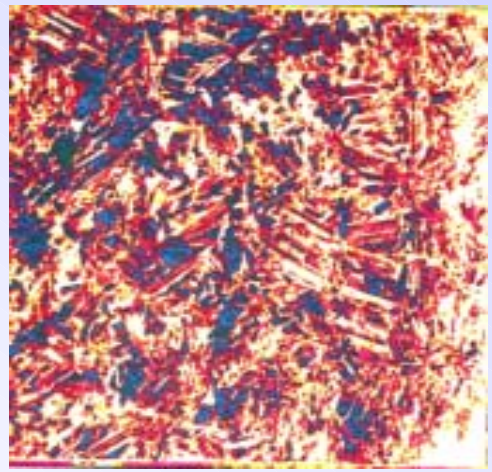
Reflectance Map



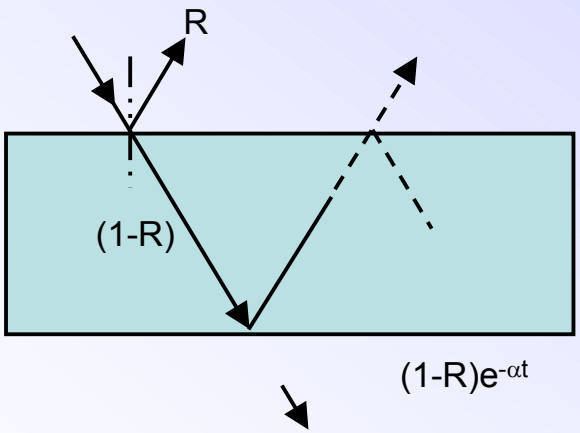
Dislocation Map

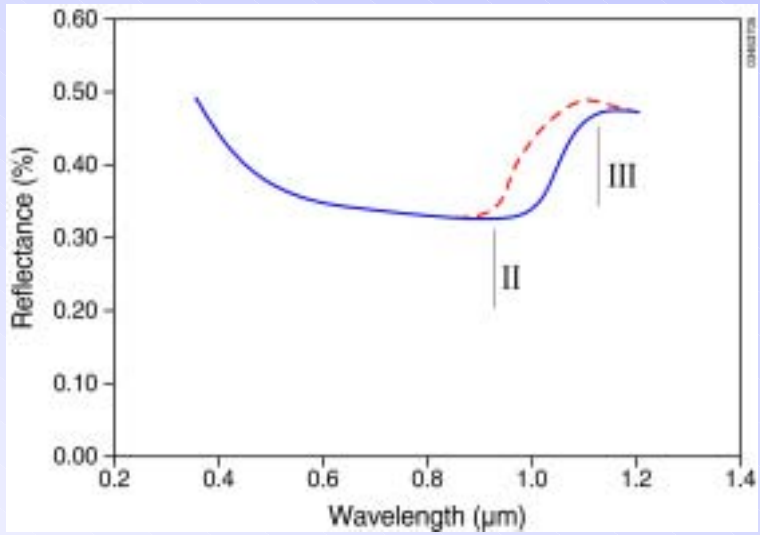


Grain Boundary Map

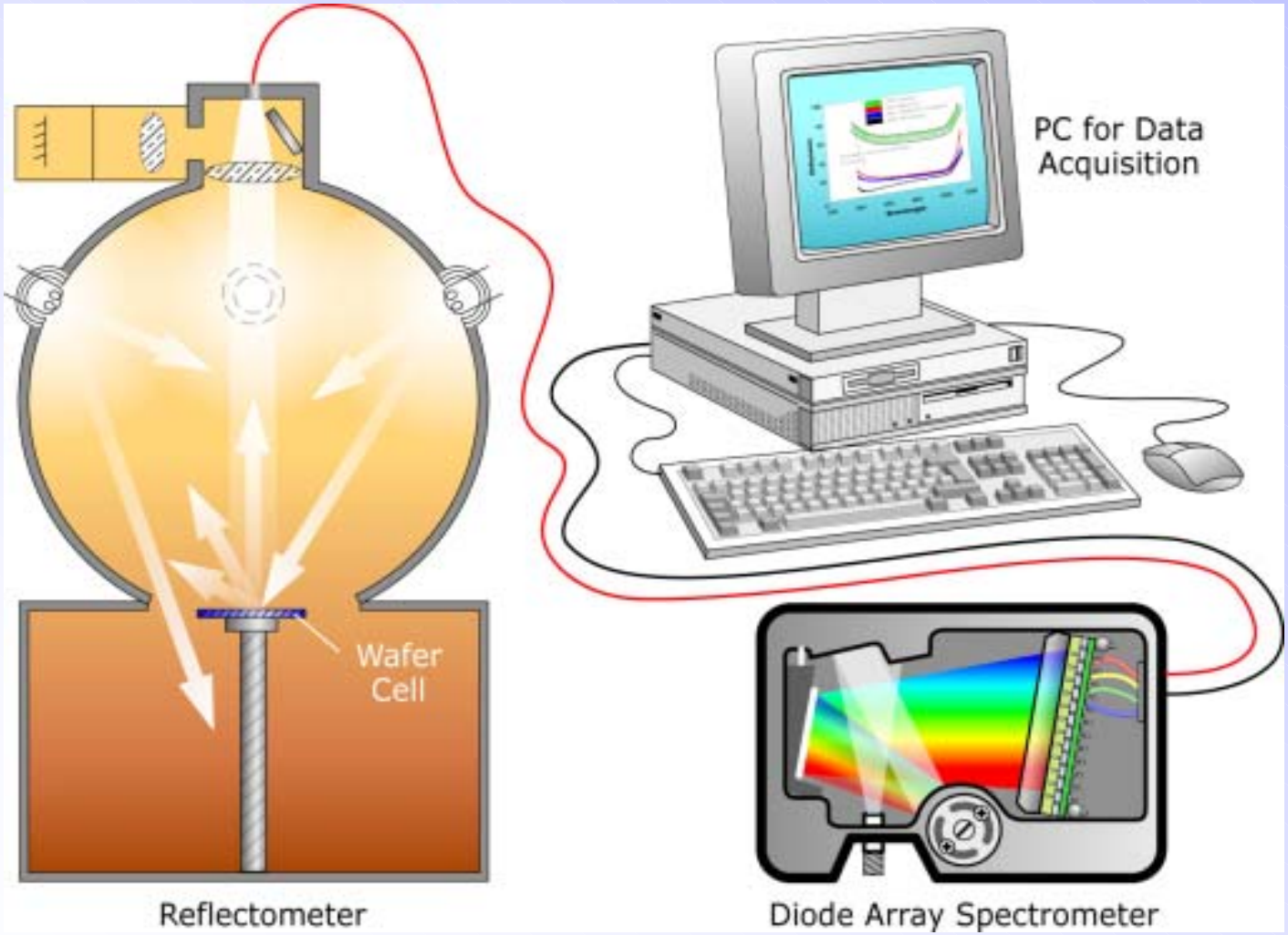


Wafer Thickness





Reflectometer



40 msec full wafer data acquisition

Solar Technology and Technology Transfer

NCPV

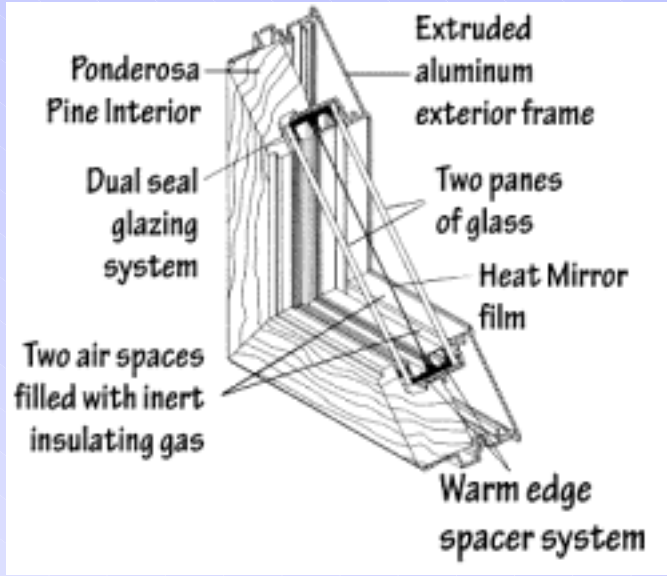
How can we make these technologies dependably available to the PV module manufacturers?

- Measurement tools improve process yields and product performance – meets industry requests
  - monitors wafer quality, saw damage, texture etch, diffusion, AR coating, contacts
  - ~$10 M annual sales
- Needs:
  - High speed wafer transport mechanism engineering
  - Manufacturing and sales
  - Reliable maintenance and technical support

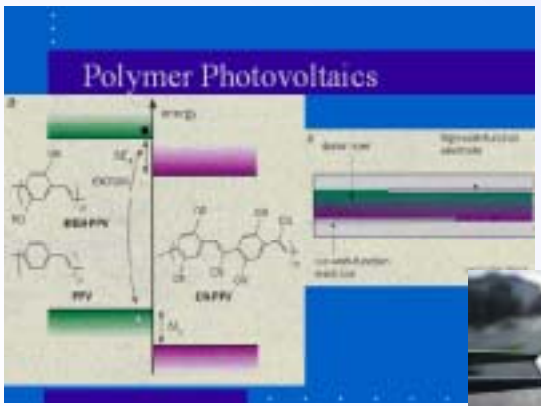
Need for New TCOs

NCPV

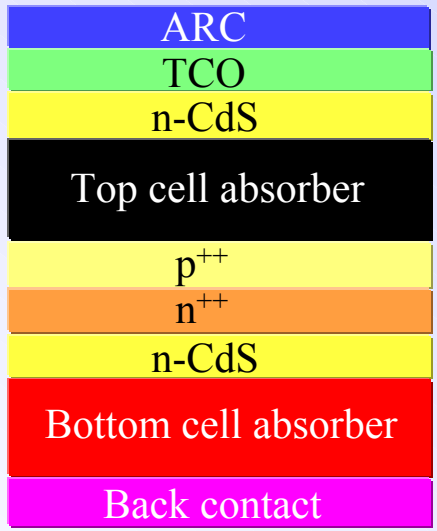
Large Area Displays



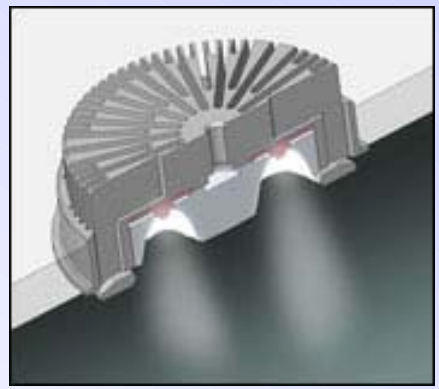
Low-e Windows



Next Generation PV



Lighting



NREL National Renewable Energy Laboratory

Discovery Mode Technologies

NCPV

Absorber		Charge Transfer
Organic/Metalorganic Dye	⟷	Nanostructured Inorganic
Inorganic particle	⟷	Inorganic matrix
Inorganic particle	⟷	Polymer
Organic particle	⟷	Polymer

Small Molecule Organic

Polymer

Tailoring properties of advanced TCO's is a critical enabling technology for all of these devices (and other applications from these materials platforms)

Transparent Conducting Oxides

NCPV

New Materials Are Needed

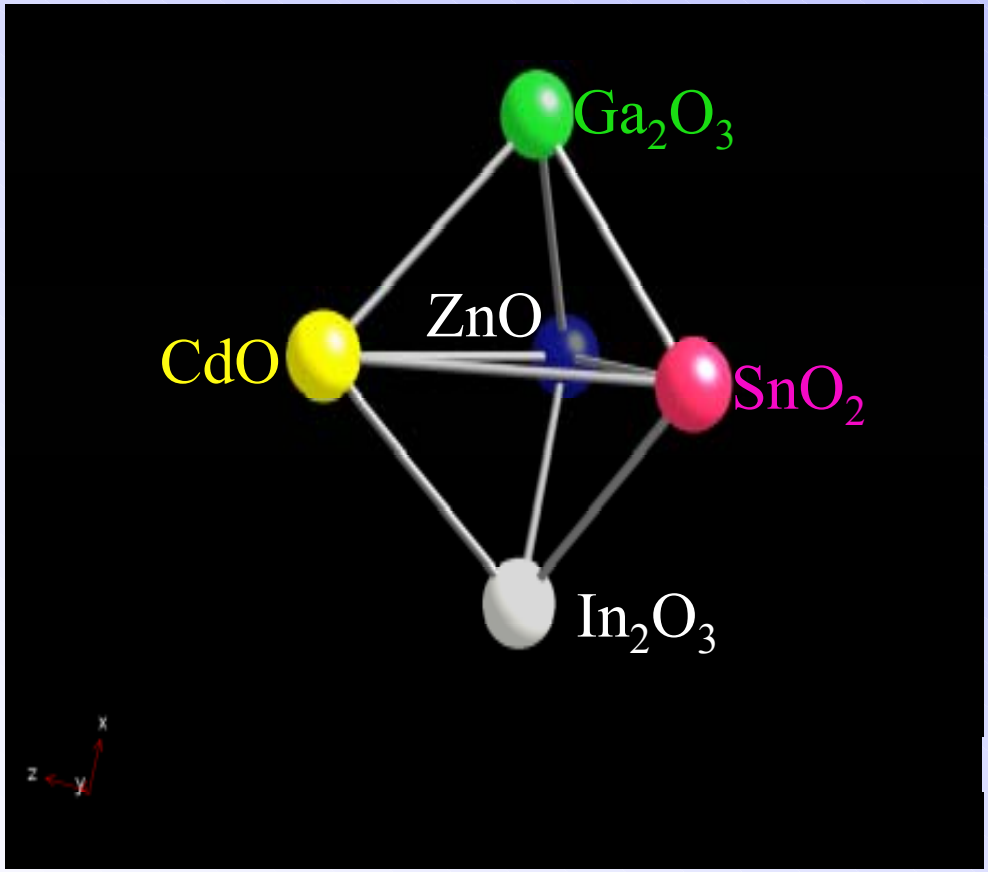
Properties

- Transmittance Visible 80-98%
- Resistivity 80-400 μΩ-cm
- Carrier Concentration 10^{19} - $>10^{21}$ cm-3
- Plasma Wavelength 1.0 – 2.0 μ
- Surface morphology atomic to Lambertian
- Work function 4.2 – 5.3 eV
- n-type and p-type Transparent Electronics, UV sources
- Other Properties: IR Transparency, Reflectivity, Etchability, Chemical Stability, Hardness, Tribology, Deposition, Temperature, Thermal Stability

… and new high thoughput materials science

Developing Capabilities for Combinatorial Materials Science @ NREL

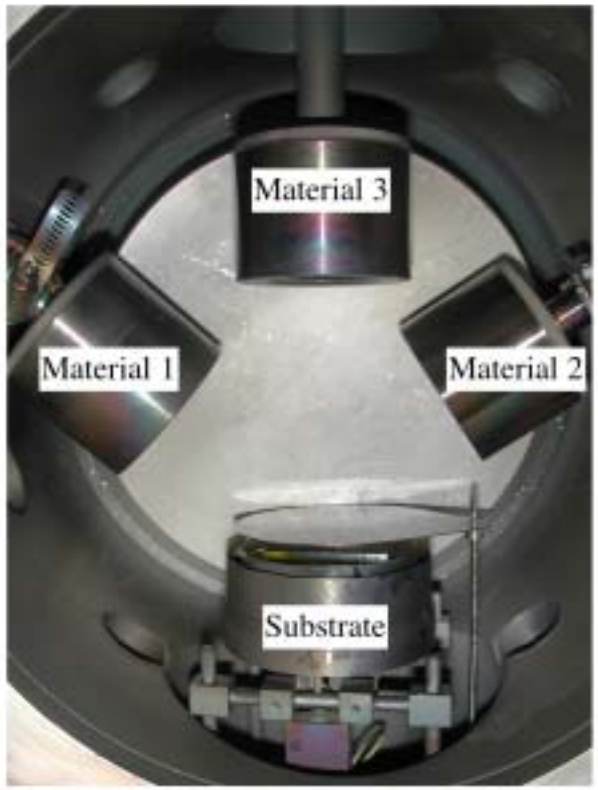
Combinatorial, Focused-Beam X-ray Diffraction

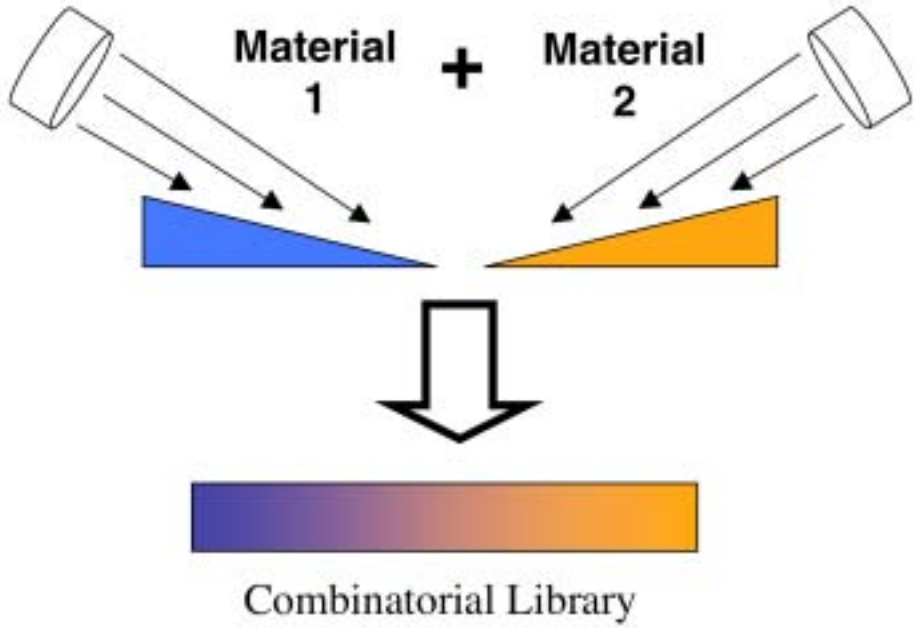


Combinatorial Oxide Deposition

NCPV

Combi Sputter I (3 guns)

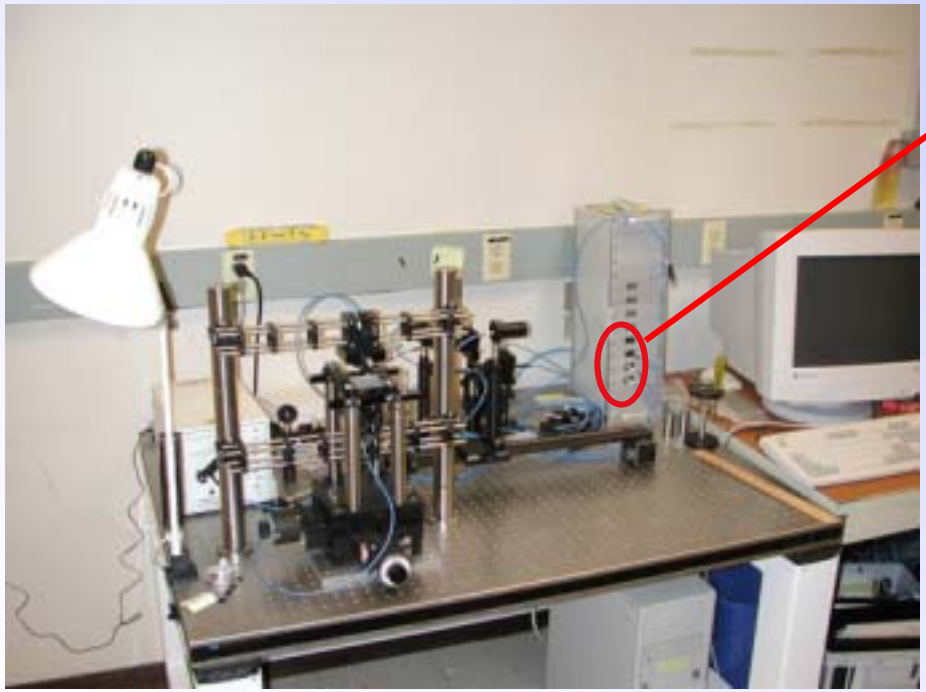


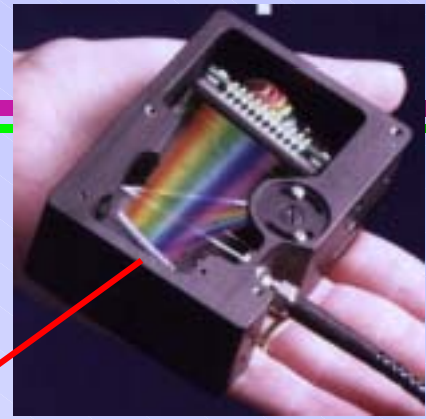


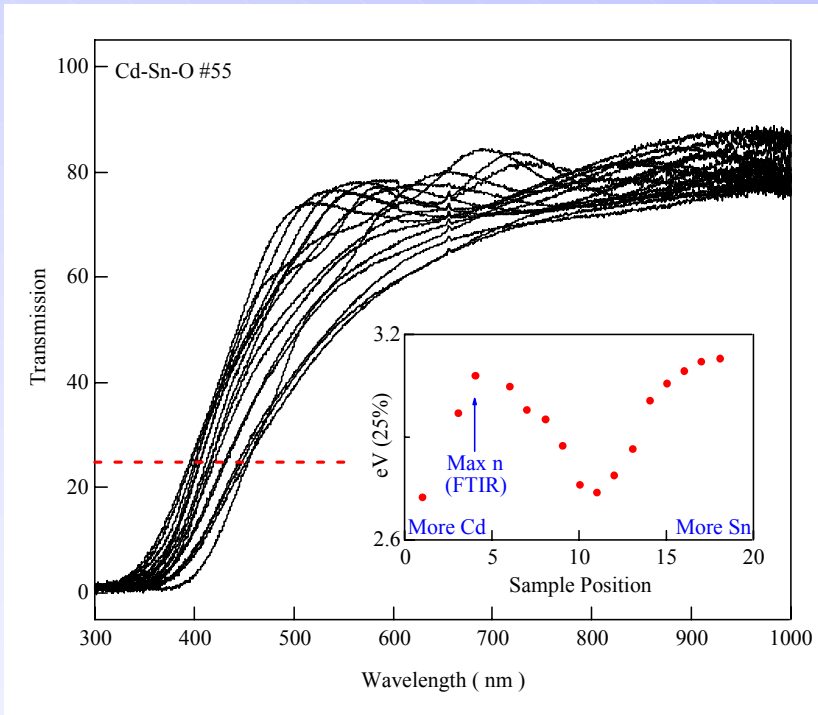
UV/VIS/NIR Transmission / Reflection

NCPV

Spectral Range: 200 - 2000 nm







Transparency and Reflectivity

Conductivity Structure Robustness

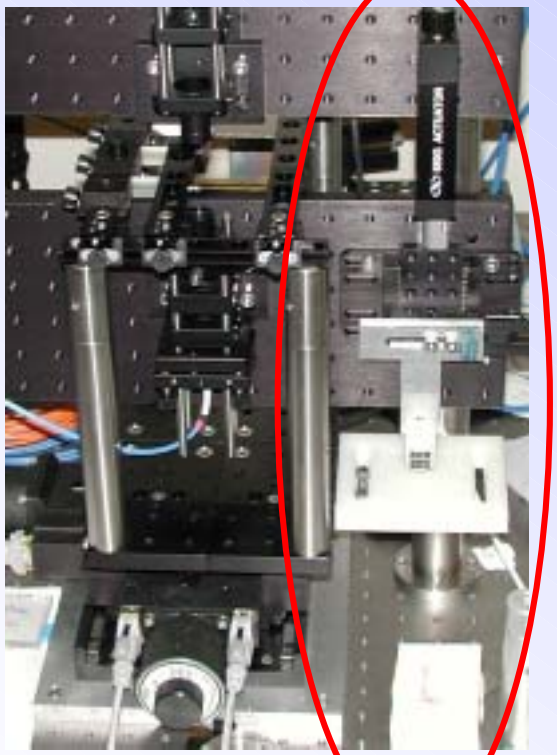
Composition

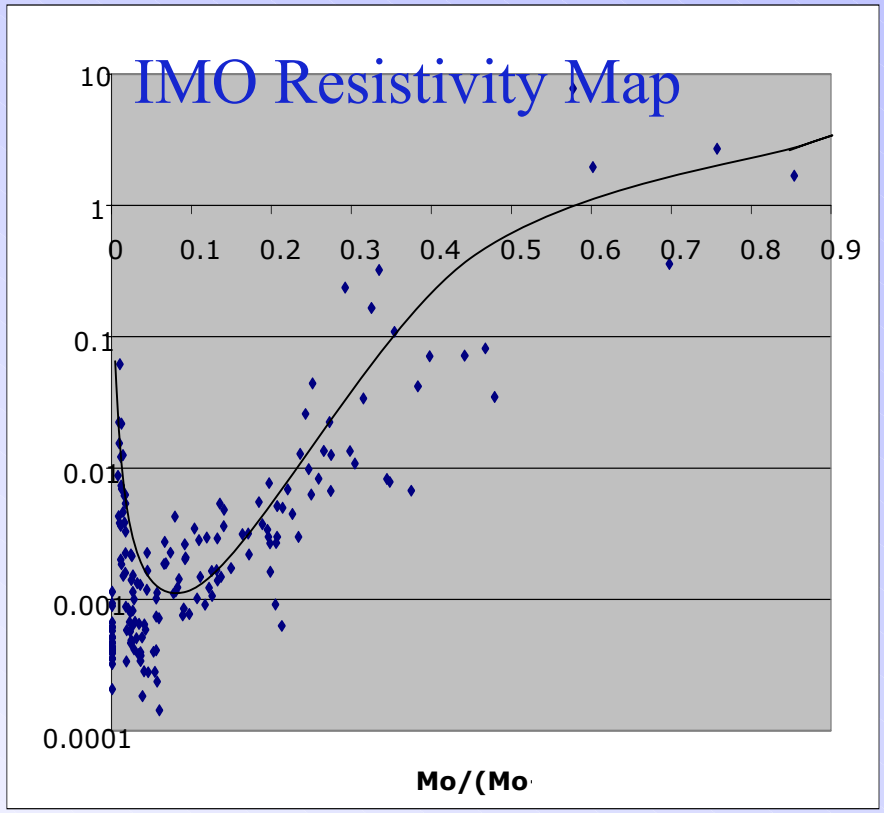
Iteration

Higher Eff. PV

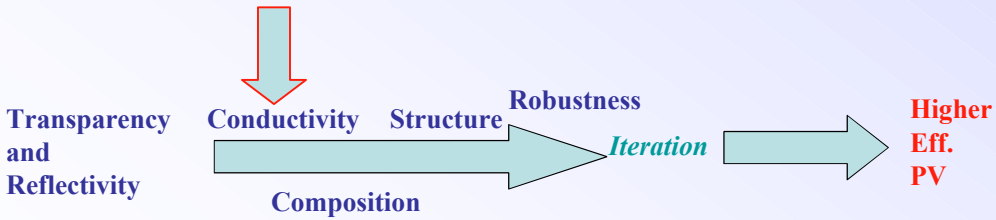
NREL National Renewable Energy Laboratory

Conductivity Mapping





4 pt probe add-on to UV/VIS/NIR mapping setup



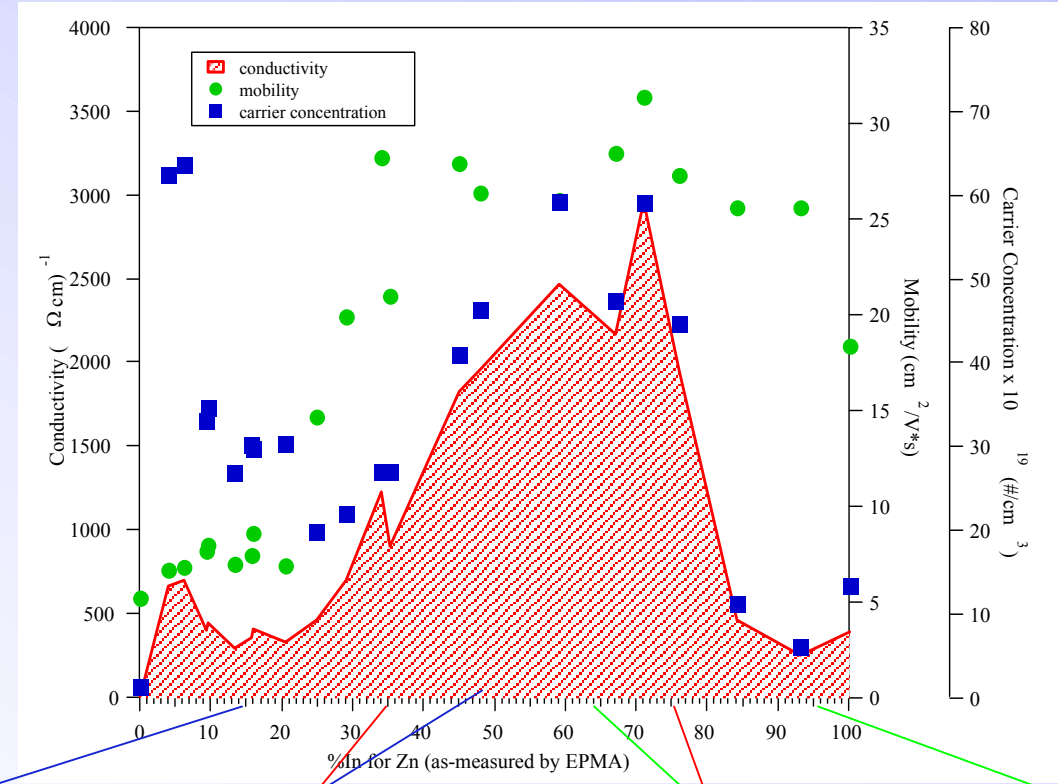
Infrared (FTIR) R, T

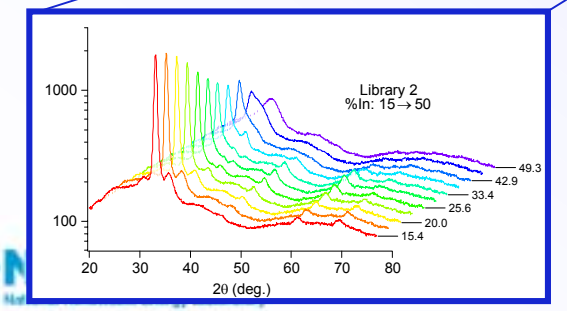
NCPV

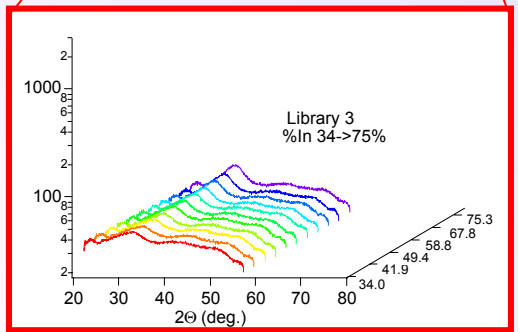
FTIR
Microscope
Transmission
Reflection

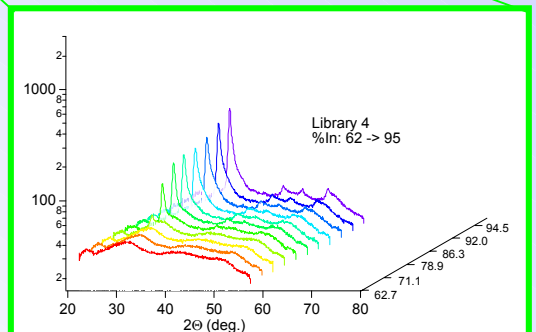
FTIR
Reflection

In_2O_3-ZnO (IZO) @ 100 °C





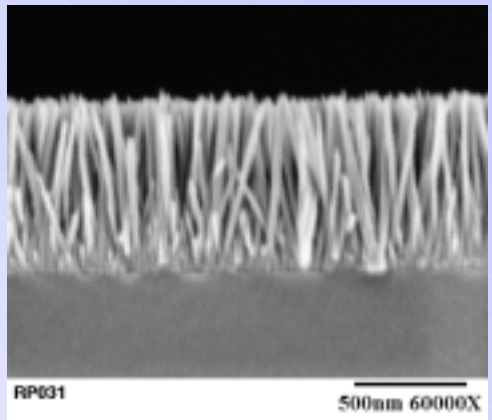




Ink Based Nanostructured Oxides

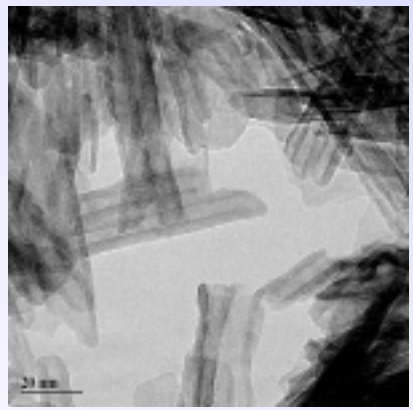
NCPV

- Synthesis of nanostructured oxides and membranes by wed chemical approaches
- Chemical modification of oxide and organic interfaces

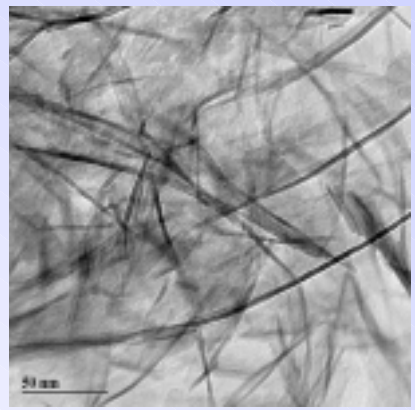


ZnO

TiO_2



Al_2O_3

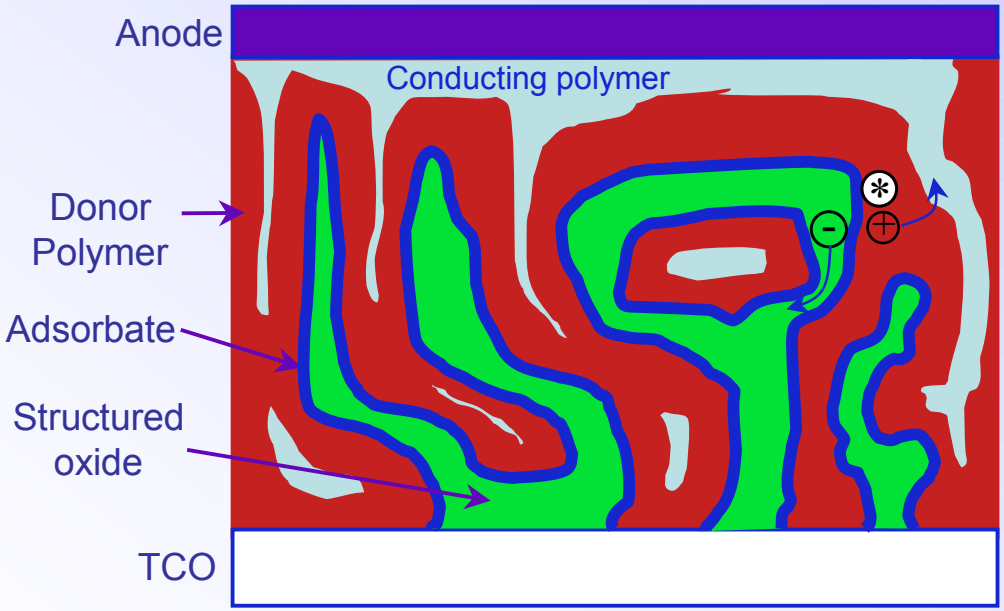


NREL National Renewable Energy Laboratory

Nanostructured oxide - polymer composites

NCPV

2-d slice of a nanostructured device concept:



Multistep charge transfer at interface:

1) $polymer^{*} + adsorbate \longrightarrow polymer^{+} + adsorbate^{-}$

2) $adsorbate^{-} + oxide \longrightarrow adsorbate + oxide^{-}$

Strengths:

- Long optical path-length
- Short carrier-to-electrode path-length
- Higher electron mobility
- No isolated clusters, guaranteed percolation
- Better adhesion between layers, mechanical durability

Weakness:

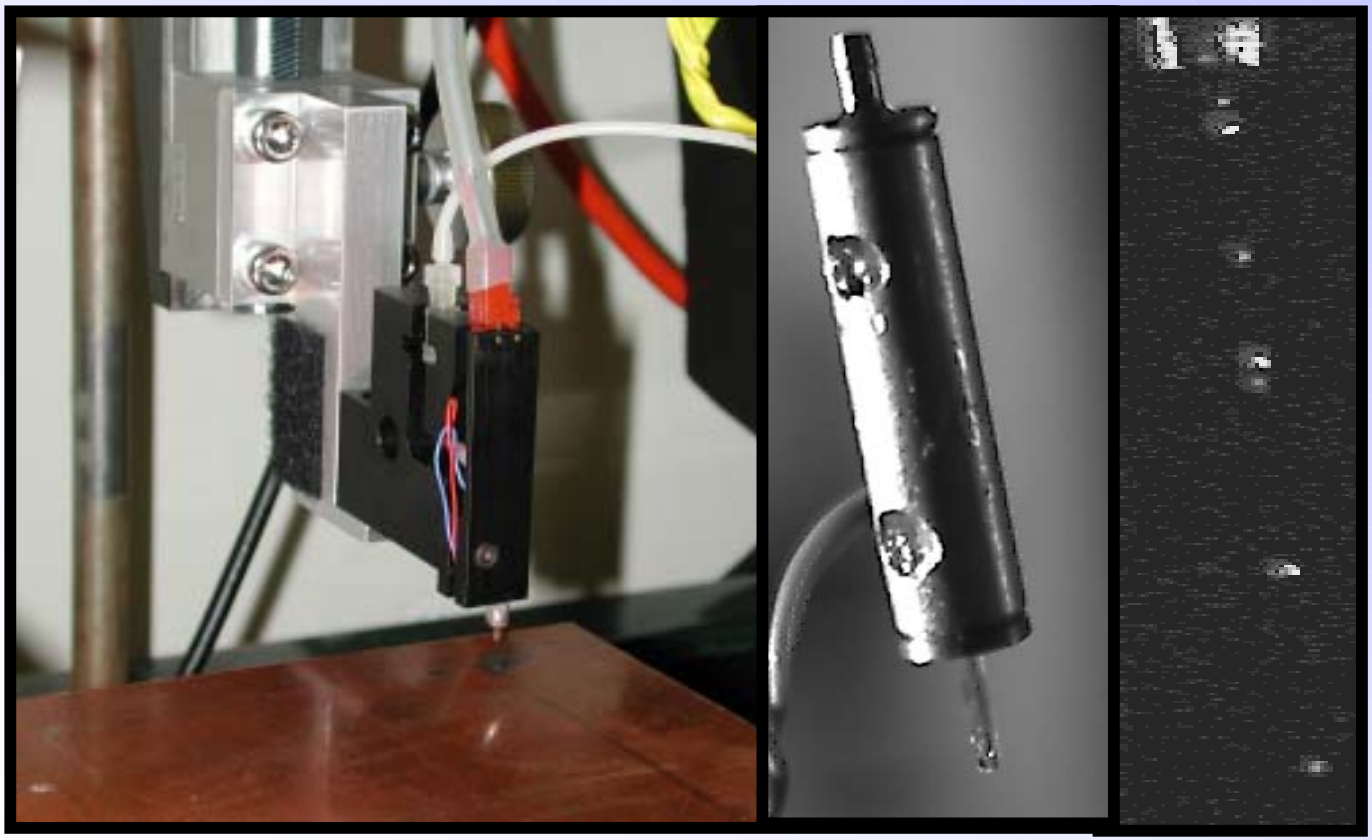
- How to fabricate?

Piezoelectric Inkjet Technology

NCPV

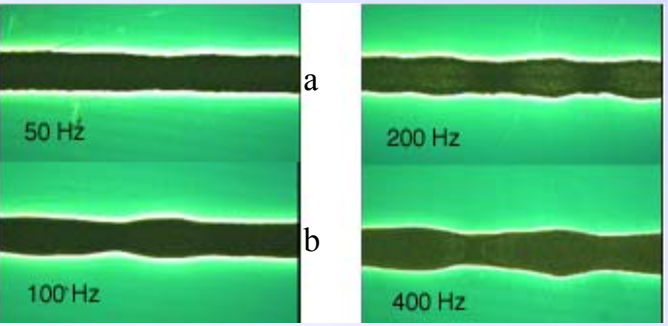
Microfab inkjet printer:

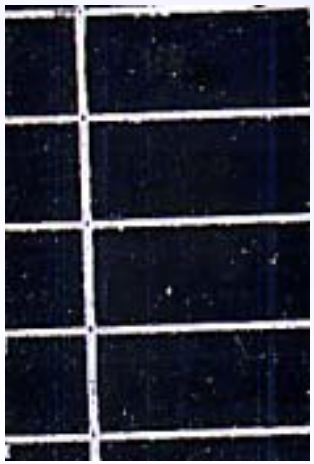
- Piezoelectric actuator
- 20, 50 μm orifice
- Drop generation rates up to 2000 Hz
- X-Y translation stage with resistive copper heater



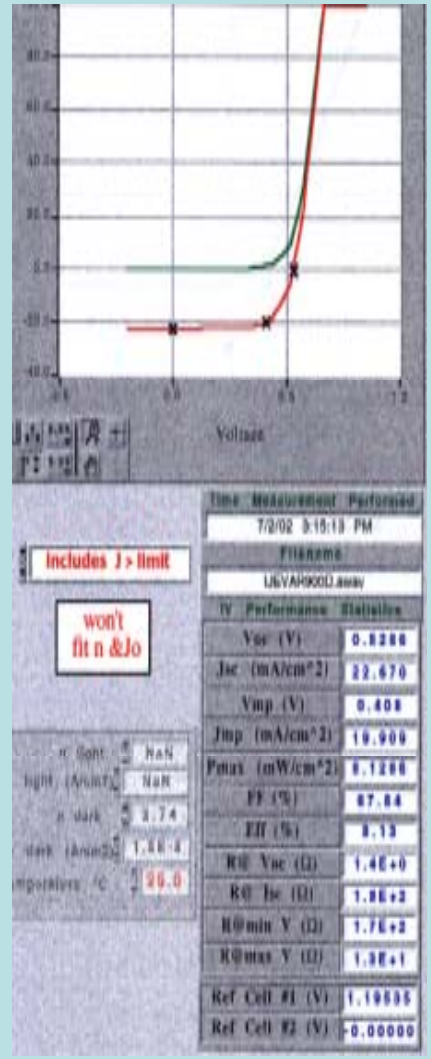
NREL National Renewable Energy Laboratory

Ink Jet Printing of Ag and Cu contacts for Si Solar Cells 8% Cells on Si_3N_4

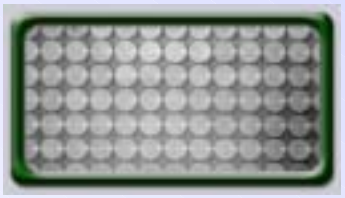




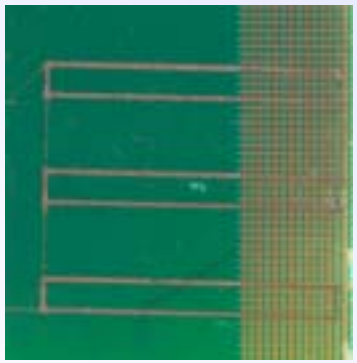
Line thickness: 15 µm
Line width: 250µm
Dep. temperature : 180 °C
Ann. temperature: 850 °C
Substrates from Evergreen Solar



Inkjet-printed Cu CRADA Microfab

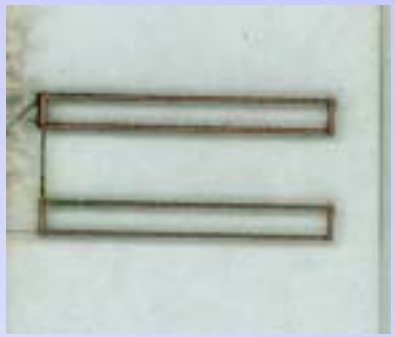


On PCB



Printed on glass, metal and Plastic Circuit Board (PCB)

On glass



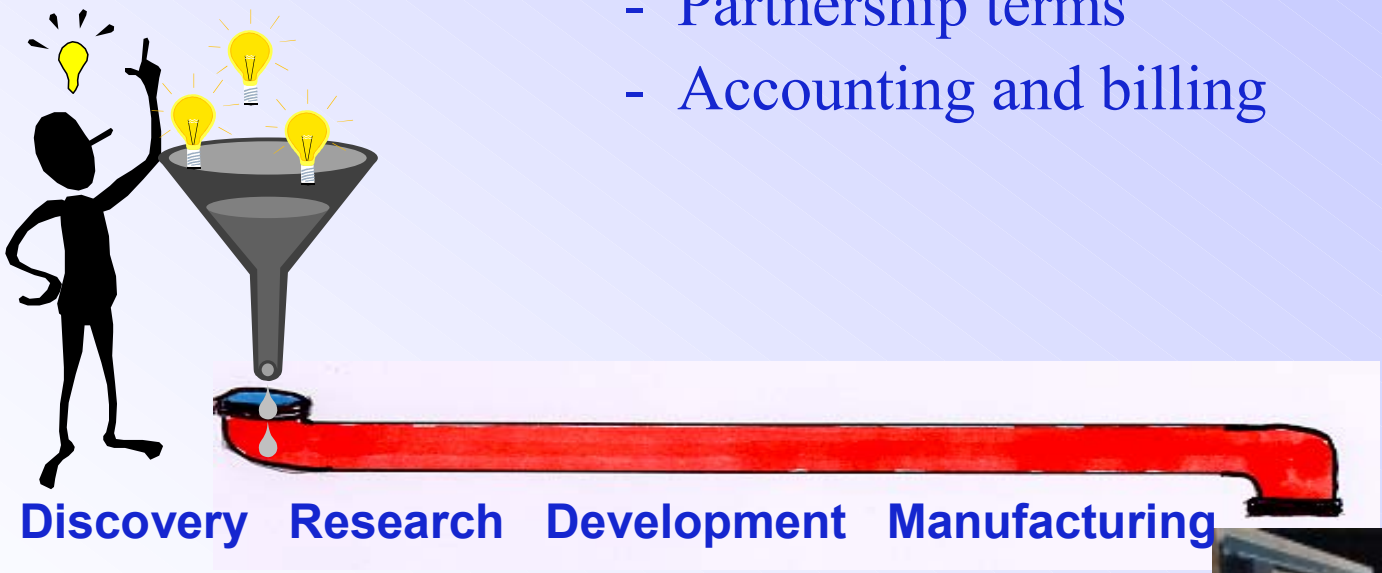
- Pure (unoxydized) Cu by rapid thermal processing in air and by printing on heated (200 °C) substrate in N_2
- Resistivity: $8*10^{-6}$ Ohm•cm (vacuum Cu $2*10^{-6}$ Ohm•cm)
- Line resolution: 250 μm for 10 μm thick line
- Deposition rate: 0.2 μm/pass

Filling the Technology Pipeline

NCPV

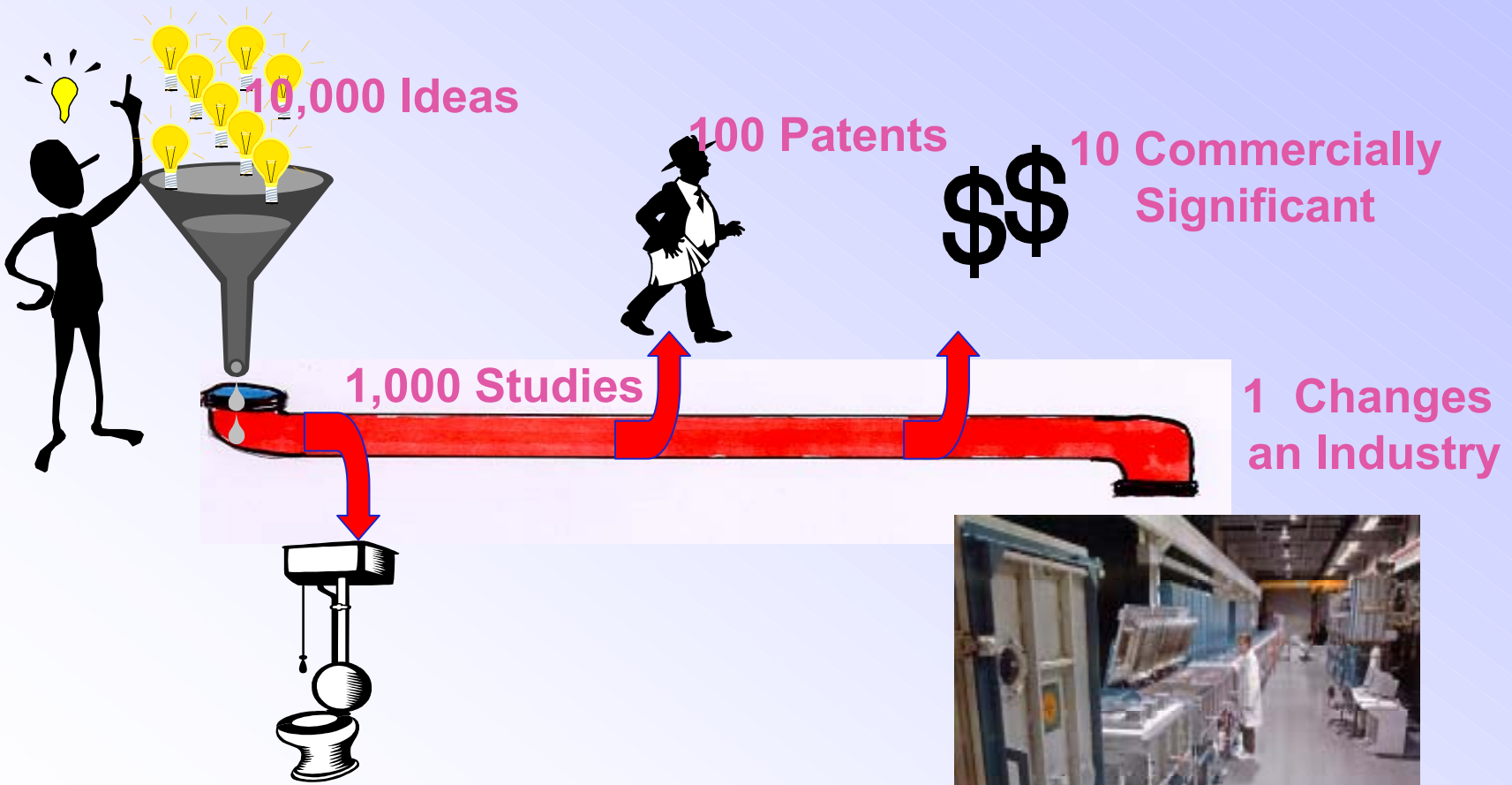
The Model For National Laboratory Performance

- Intellectual property control
- Partnership terms
- Accounting and billing



NREL National Renewable Energy Laboratory

“Rule of Tens”


10,000 Ideas
100 Patents
$$
10 Commercially Significant
1,000 Studies
1 Changes an Industry

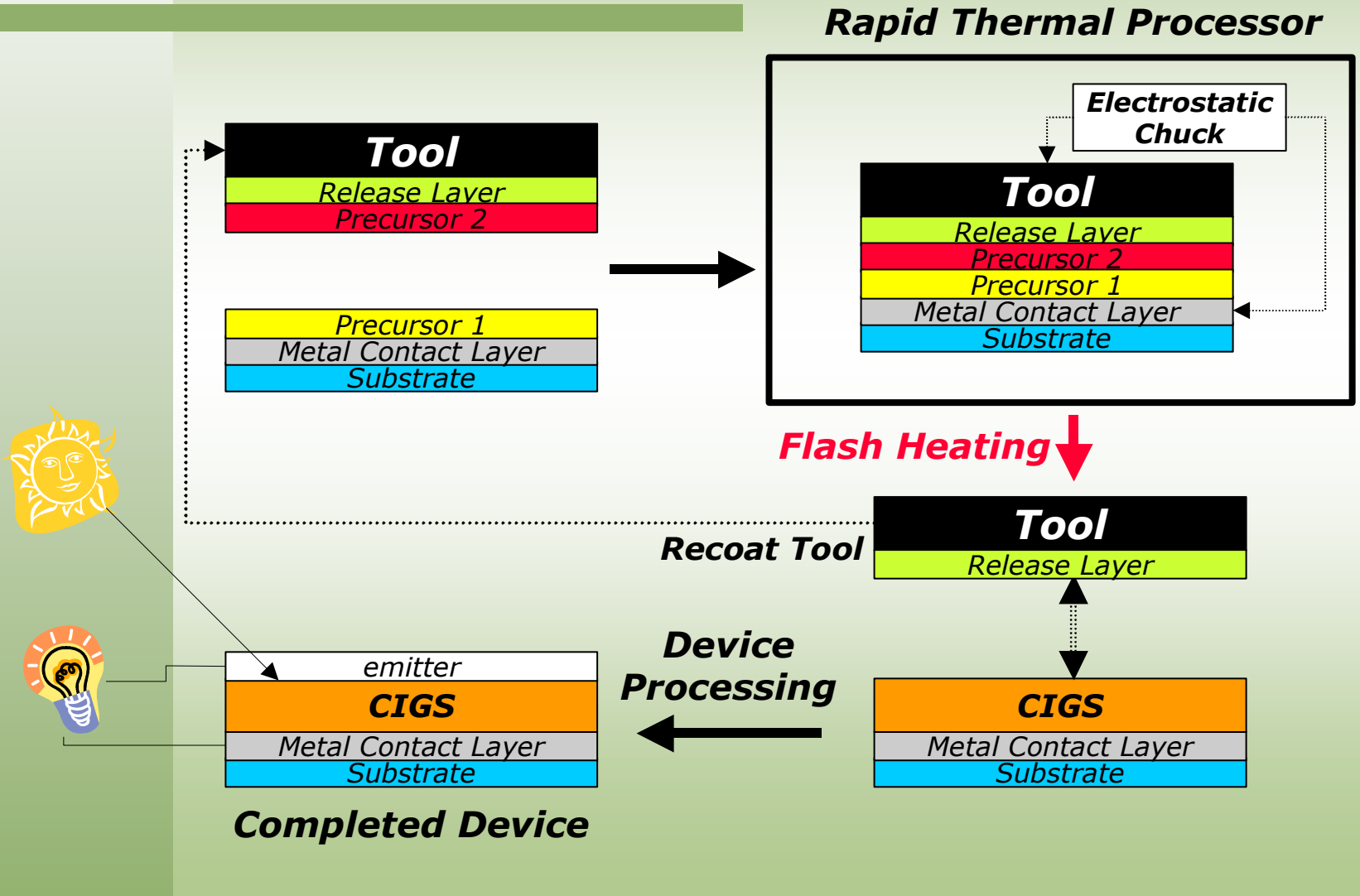
Innovation in Industry Partnerships

NCPV

- CRADA, TSA, ASA, NDA, MOU
- On-site shared operation of equipment
- Equipment loans
  - From and To NREL
- Web served protected data exchange

HelioVolt CRADA

FASST™



PECVD Processing for CIGS
Applied Materials -AKT CRADA

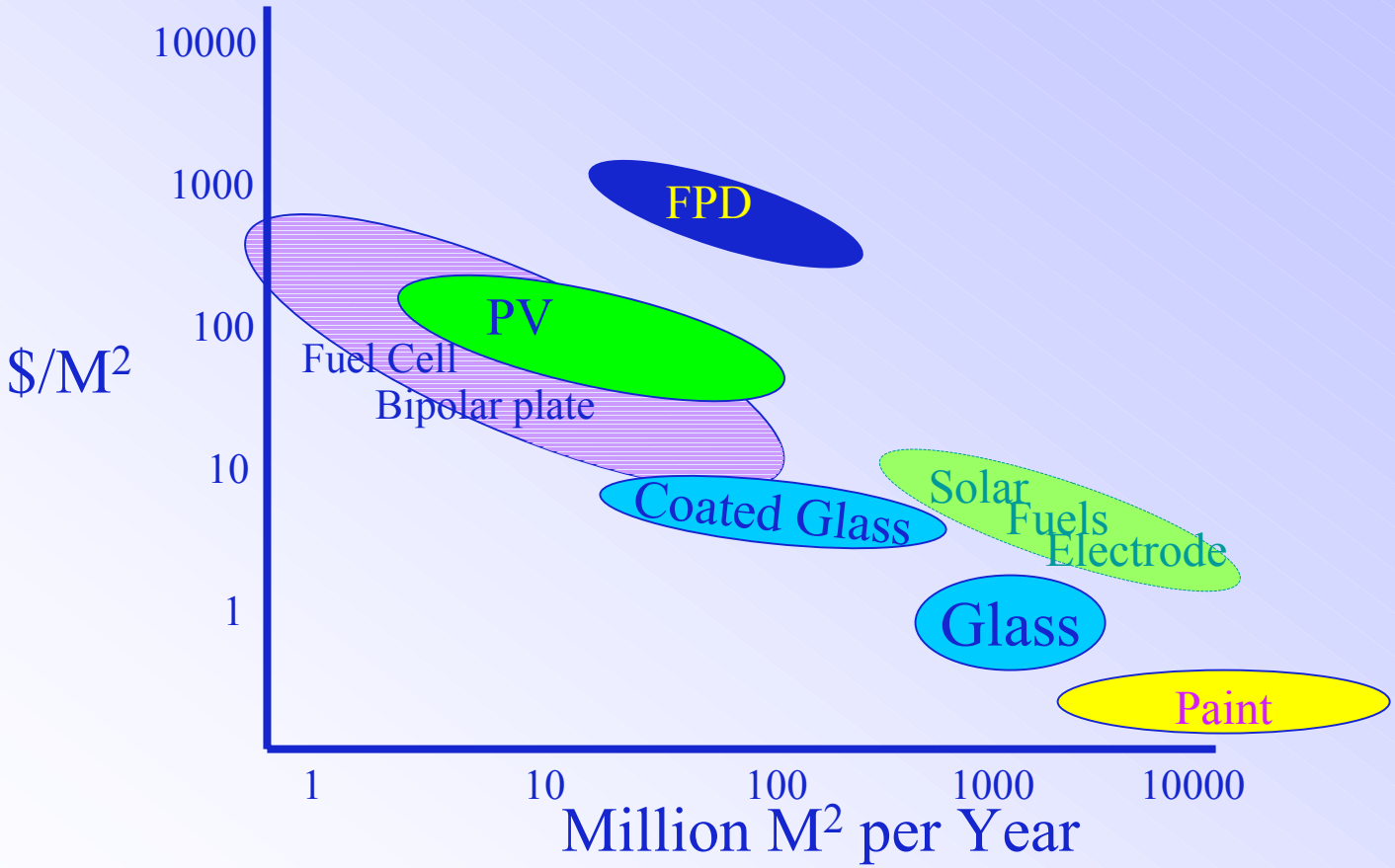
- CIGS Films (at NREL)
- Window TCO Films (at NREL)
- Window/Buffer Interface Films (at NREL)
- Buffer Film (at NREL)
- Mo Metal Film (at AKT)
- AR Coating Film (at AKT)

Low Cost Processes

Space PV

LED

Large-Area Optical and Electronic Materials



Silicon Feedstock and Wafers

NCPV

CRADA GTi CVD Process

TSA Crucible Evaluation

Solaicx™

License NREL Silicon Purification by Iodine Chemical Vapor Transport with R-Wave

NREL National Renewable Energy Laboratory

Keeping Pace with the Entrepreneurs

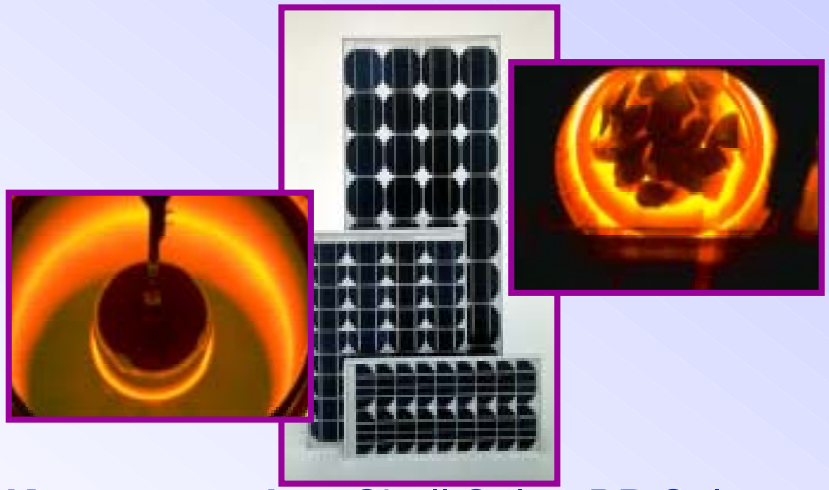
NCPV

- Industry is losing the maturity of shared marketing resources (How can we help keep track of reality?)
- Improve coordination among entrepreneurs, investors and NREL (How to best "invest" our credibility?)
- Input for improving evaluation of NREL technologies (Have we made good research investments?)

Back-up material for PV

Crystalline Silicon (Ingot-Based) PV

NCPV



- **Key companies:** Shell Solar, BP Solar, AstroPower; Sharp, Kyocera, Sanyo, Motech, Cypress-SunPower
- ~85% of today's market
- ~400 MW capacity (to double in near-term)
- Proven products, 20-25 year warranties
- Large ingots: 100 kg CZ, 250 kg casting
- Multiple ingot growth with melt replenishment
- Wire saw: < 250 µm wafers, < 200 µm kerf

Efficiency Status	**Cells**	**Modules**
Float-zone	24.7	22.7*
Czochralski	22.0	13–176
Cast poly	19.8	10–13

- Batch/continuous processing
- High-efficiency devices in production
- Well-developed technology base--new understanding of defects/impurities

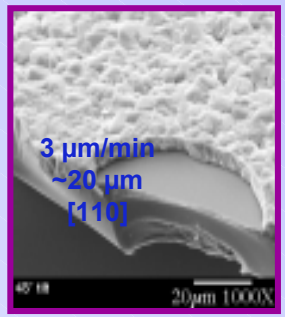
* Best prototype

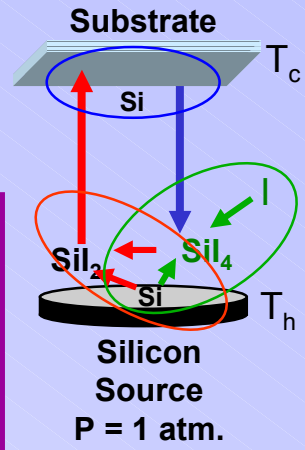
02679603

NREL National Renewable Energy Laboratory

Crystalline Silicon (Non-Ingot-Based) PV

NCPV





- **Key companies:** RWE Schott Solar, Evergreen Solar, AstroPower, Pacific Solar, Kaneka
- Status varies from prototype modules to pilot production to commercial products (many MW)
- Proven products (~ 6% of market)
- Capacity increases underway—many tens of MW in near term

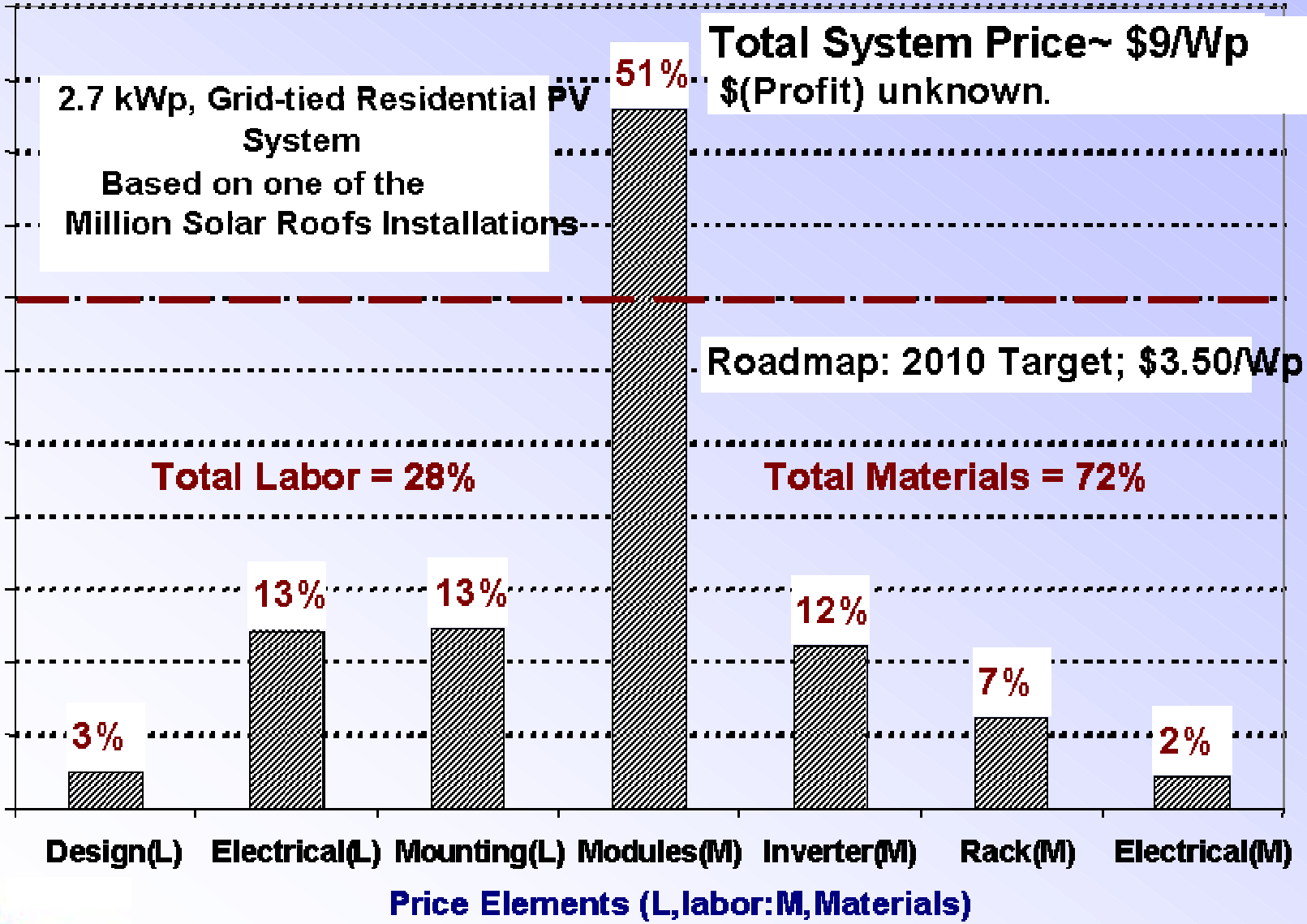
Efficiency Status	**Modules**	**Cells**
EFG	14–16	11–13
String ribbon	14–16	10–12
Thick Si/substrate	16.6	9–10
Thin Si/substrate	5-12*	~ 7**

- Improved performance from defect/impurity and passivation studies
- Increasing interest in thin silicon growth

- * Depends on process (some efficiencies not verified)
- ** Best prototype

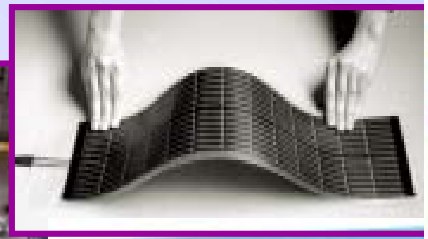
NREL National Renewable Energy Laboratory

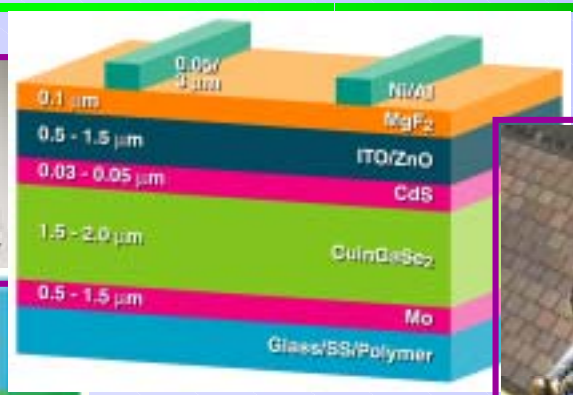
Breakout of Installed Price of a Residential PV System by %

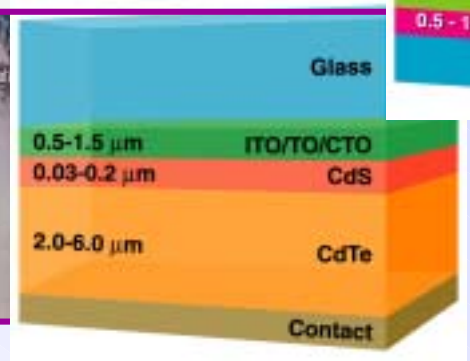


Thin-Film PV

NCPV







Key companies: United Solar/ ECD, Shell Solar, EPV, Global Solar/ITN, First Solar, Iowa Thin Films, HelioVolt, Wurth Solar, Showa-Shell, DayStar, Miasolé

- Multi-MW/year in consumer products
- 5 and 10 MW plants operational; few tens of MW in near term
- Unique products for building integration

Efficiency status:

Cell	12-19
Submodule	10-12
Module	7–11
Commercial	5–10

- Understanding of film growth, microstructures, defects, and device physics
- Reproducible high-efficiency processes
- Multiple junctions

02679607

NREL National Renewable Energy Laboratory

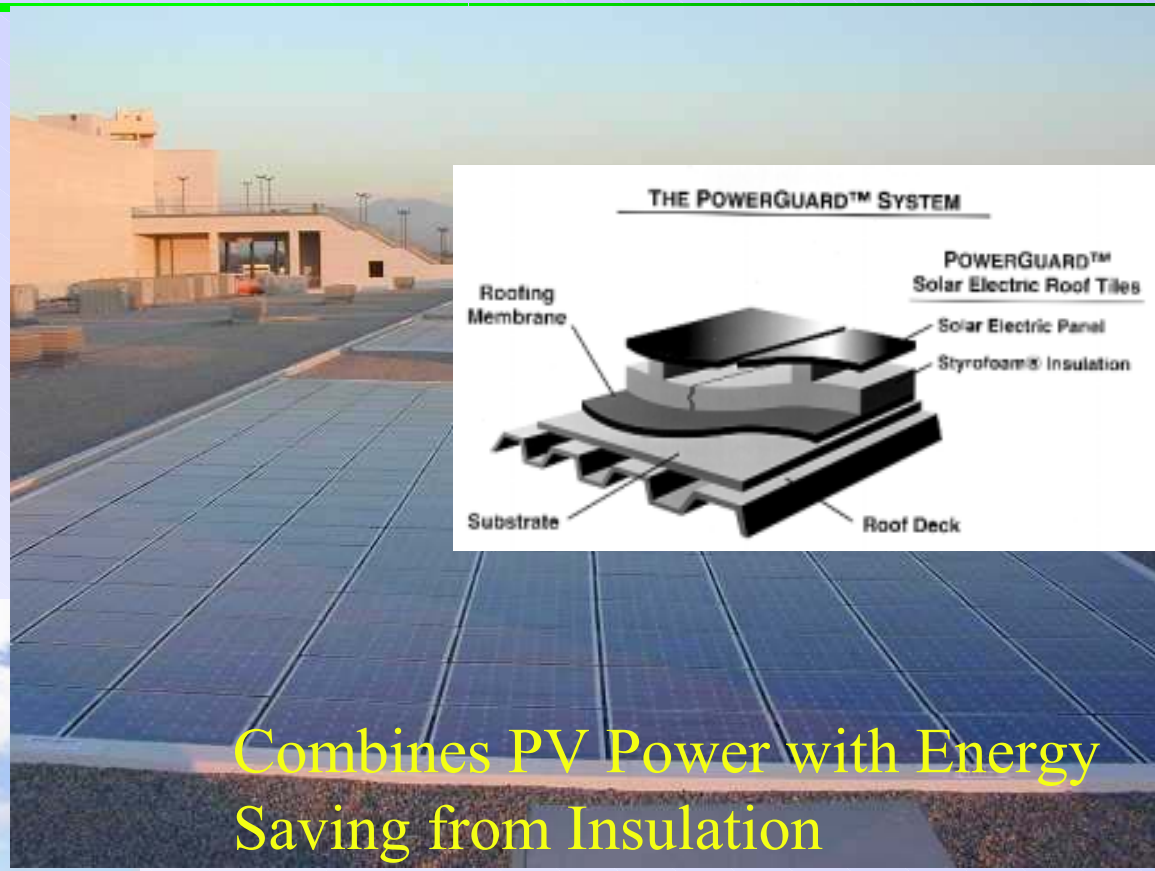
Conventional PV Installations

NCPV

Powerlight Roof Integrated PV System

NCPV

Advances in PV System Design Can Also Achieve Cost Advantages

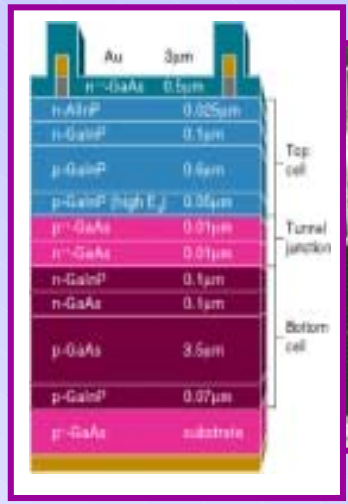


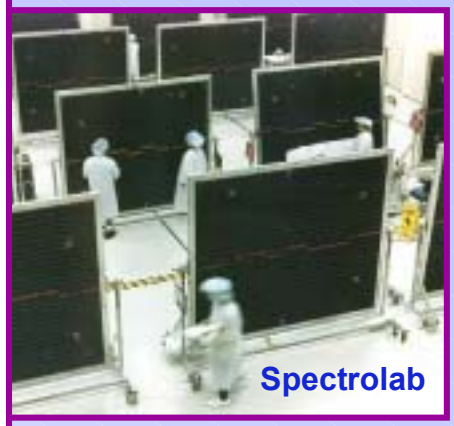
Combines PV Power with Energy Saving from Insulation

United Solar Shingles

High-Efficiency and Concentrator PV

NCPV





Key companies: Amonix, Spectrolab, Emcore, Sunpower, ENTECH; Solar Research Corp. (Australia)

- Manufacturability demonstrated
  - Low-concentration, line focus
  - High-concentration, point focus
  - High efficiency cells (Si, GaAs, multijunctions) in production
- Limited applications in today's markets
  - Hydrogen generation may be well matched

Efficiencies:

Si (up to 400X)	27
GaAs (up to 1000X)	28
$GaInP_2$/GaAs (1X)	30.3
$GaInP_2$/GaAs (180X)	30.2
$GaInP_2$/GaAs/Ge (40–600X)	36.9

- Module efficiencies: 15-17% (Si); best prototypes: >20% (Si), >24% (GaAs), 28% ($GaInP_2$/GaAs/Ge,10X)
- Large space markets drive $GaInP_2$/GaAs and $GaInP_2$/GaAs/Ge commercial cell production

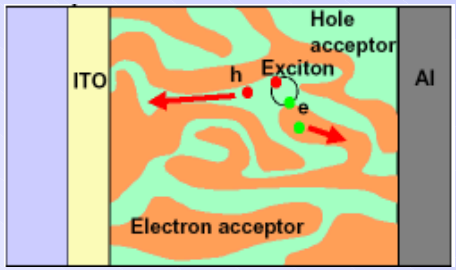
02679613

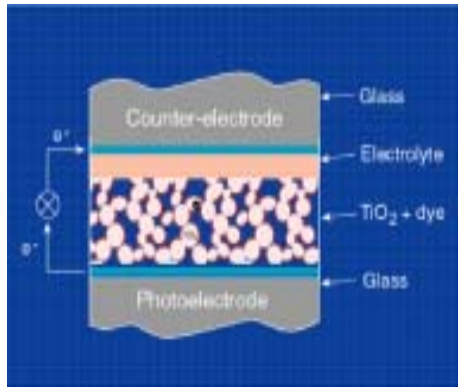
NREL National Renewable Energy Laboratory

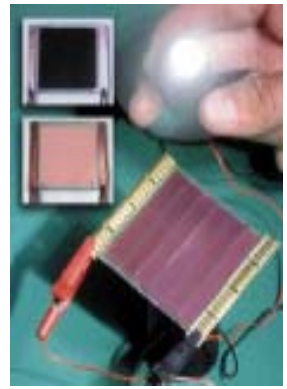
Novel Concepts, Excitonic Devices and New Materials

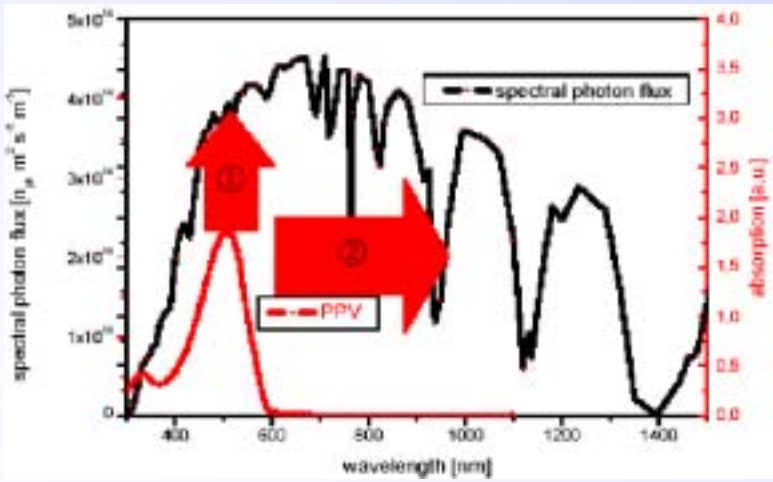
NCPV

- **Key Companies:**
  GE, Kodak, Konarka, NanoSolar, NanoSys, Luna, UltraDots …









Light management	• Enhanced absorptivity of dyes • Low bandgap polymers
Reduce series resistance	• Higher mobility polymers • Enhanced TCOs • Electrolyte formulations • Polymer morphology

- **Dye-sensitized TiO_2 photochemical cells**
- Potential for very low cost
- Nanocrystalline TiO_2, with monolayer dye sensitizer,in liquid electrolyte
- 11%-efficient cell; scale-up for consumer products underway
- Dye stability issue
- Gel or solid-state electrolytes in research
- Photoelectrochromic window (with WO_3)

02679615

NREL National Renewable Energy Laboratory